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(KP 1701)

ANALISIS PENGARUH PEMBERIAN POTENSIAL NEGATIF DALAM PROSES PERLINDUNGAN KATODIK TERHADAP FRACTURE TOUGHNESS BAJA SS 41

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Surabaya, 17 Juli 2001

Mengetahui dan Menyetujui

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#ANALISA PENGARUH PEMBERIAN POTENSIAL NEGATIF DALAM PROSES PERLINDUNGAN KATODIK TERHADAP FRACTURE TOUGHNESS BAJA SS-41#

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INSTITUT TEKNOLOGI SEPULUH NOPEMBER

ABSTRAK

FAKULTAS TEKNOLOGI KELAUTAN

JURUSAN TEKNIK PERKAPALAN

Sarjana Teknik (S1)

ANALISIS PENGARUH PEMBERIAN POTENSIAL NEGATIF DALAM PROSES PERLINDUNGAN KATODIK TERHADAP *FRACTURE TOUGHNESS* BAJA SS-41

Oleh : Mukti Syarif Rivai

Pembimbing : Wing Hendroprasteyo Akbar Putra, ST , M.Eng.

Structural Steel SS-41 adalah material yang umum digunakan pada bangunan laut. Pada struktur tanpa lapisan pelindung, perlindungan korosi dilakukan dengan metode *impressed current cathodic protection*. Kegagalan struktur yang terjadi pada konstruksi bangunan laut yang menggunakan metode ICCP diduga terjadi karena adanya pemberian potensial negatif yang berlebihan pada proses perlindungan katodik yang menyebabkan meningkatnya konsentrasi hydrogen di sekitar struktur.

Kehadiran hydrogen ini dapat memicu terjadinya *hydrogen damage* pada material yang dapat menurunkan ketangguhan (*toughness*) material. Pengujian ini dilakukan untuk mengetahui pengaruh potensial negatif yang berlebihan pada proses perlindungan katodik terhadap *fracture toughness* baja SS-41.

Dalam tugas akhir ini pengujian *fracture toughness* dilakukan menggunakan standard ASTM *Volume* 03.01 *designation*: E 399-83 terhadap baja SS-41 yang sebelumnya diberi potensial perlindungan katodik melalui pengujian sel tiga elektroda. Masing-masing spesimen diberi potensial negatif yang berbeda-beda sebesar -850, -950, -1050, dan -1150 mV SSC selama 7 hari (168 jam).

Hasil pengujian menunjukkan adanya penurunan *fracture toughness* baja SS-41 yang berkisar antara 2,08 % sampai dengan 16,67 % setelah pemberian potensial negatif yang berlebihan.

ABSTRACT

Structural steel SS-41 is the most common material that used for offshore structures. Impressed Current Cathodic Protection (ICCP) method is used to protect the uncoated structures from corrosion. Mechanical failure occured in the structure using ICCP may be caused by the effect of cathodic overprotection that may have increased hydrogen concentration around the structures.

The increasing of hydrogen concentration teoritically cause hydrogen damage that may decrease material toughness. These experiments were carried out to know the effect of cathodic overprotection to the fracture toughness of SS-41 steels.

By using ASTM standard, E 399-83; the fracture toughness testing were applied to SS-41 steels which have been impressed by –850 mV SSC, -950 mV SSC, -1050 mV SSC, -1150 mV SSC for 7 days (168 hours).

As a result, it was apparent that there were a decrease in fracture toughness on the range betwen 2.08% to 16.67%.

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ANALISIS PENGARUH PEMBERIAN POTENSIAL NEGATIF DALAM PROSES PERLINDUNGAN KATODIK TERHADAP *FRACTURE TOUGHNESS* BAJA SS-41

Tugas akhir ini merupakan salah satu prasyarat untuk menyelesaikan studi kesarjanaan strata satu (S-1) di Jurusan Teknik Perkapalan, Fakultas Teknologi Kelautan, Institut Teknologi Sepuluh Nopember Surabaya.

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A	Luas penampang
A	Panjang retak
a_{eff}	Panjang retak efektif
a_o	Panjang retak spesimen uji
B	Tebal spesimen
b, b_o	*Uncrack ligamnet*
E	Modulus elastisitas pada tarikan (*tension*) dan desakan (*compresion*)
G	Modulus elastisitas pada geser (*shear*)
G_{Ic}	*Crack extension force*
K	Faktor intensitas tegangan (SIF)
K_c	*Fracture toughness plane-stress*
K_{Ic}	*Fracture toughness plane-strain*
K_Q	*Fracture toughness perhitungan*
K_I, K_{II}, K_{II}	Faktor intensitas tegangan mode I, mode II , mode II
L	Panjang spesimen
N	Lebar retak
P	Beban atau gaya luar
P_{max}	Beban maksimum
P_Q	Beban pada offset 5%
R	*Strenght ratio*
r	Koordinat kutub
r_p*	Ukuran daerah plastik
r_y	Jari-jari zona plastik
u, v, w	Komponen perpindahan dalam arah x, y, z
v_p	Komponen plastik clip gage displacement
W	Lebar spesimen
z	Jarak permukaan retak terhadap ujung alat pengukur
β_{Ic}	*Irwin plane-strain*
δ	*Crack tip opening displacement* (CTOD)

γ	Regangan geser
Δ	*Displacement*
$\Delta a_{p\ min}$	*Crack extension minimum*
$\Delta a_{p\ max}$	*Crack extension maximum*
θ	Koordinat kutub
υ	Rasio poisson
σ	Tegangan normal, tegangan sesungguhnya
σ_F	Tegangan fracture
σ_{flow}	Setengah dari jumlah tegangan yield dan tegangan ultimate
σ_{net}	*Net section stress*
σ_{ult}	Tegangan *ultimate* (maksimum)
σ_y, σ_{ys}	Tegangan *yield* (luluh)
$\sigma_x, \sigma_y, \sigma_z$	Komponen tegak lurus dari tegangan yang sejajar dengan sumbu-sumbu x, y, z
$\tau_{xy}, \tau_{xz}, \tau_{yz}$	Komponen tegangan geser dalam koordinat persegi panjang

BAB I

PENDAHULUAN

BAB I

PENDAHULUAN

1.1 Latar Belakang

Kegagalan mekanis dapat didefinisikan sebagai perubahan dalam dimensi, bentuk atau *material properties* dari suatu struktur yang menyebabkan ketidakmampuan struktur tersebut untuk berfungsi sesuai dengan yang direncanakan.

Seorang *engineer* harus dapat merencanakan struktur yang berfungsi baik selama umur pakainya, memenuhi faktor keselamatan dan ekonomis. Mode-mode kegagalan yang mungkin terjadi pada struktur harus mendapat perhatian serius untuk dihindari.

Kapal dan bangunan laut lainnya yang terbuat dari baja beroperasi pada lingkungan yang korosif, sehingga sangat rentan terhadap kegagalan mekanis akibat penurunan kualitas baja yang disebabkan oleh terjadinya korosi. Korosi diartikan sebagai kerusakan, keausan atau penurunan mutu logam atau material yang diakibatkan oleh terjadinya reaksi elektrokimia dengan lingkungan yang didukung oleh faktor-faktor tertentu [Trethewey dan Chamberlain, 1991].

Korosi yang terjadi akan menimbulkan kerusakan dan mengakibatkan kerugian baik segi ekonomis maupun segi keselamatan. Karena itu dibutuhkan suatu cara untuk memperlambat laju korosi. Salah satu cara untuk mengurangi laju korosi dari suatu material adalah perlindungan katodik yang terdiri atas dua

metode, yaitu: metode arus terpasang (*impressed current*) dan metode anoda tumbal (*sacrificial anode*) [Chandler, 1985]. Pada metode arus terpasang, perlindungan dilakukan dengan pemberian potensial negatif terhadap struktur yang beresiko mengalami korosi. Semakin besar potensial negatif yang diberikan pada logam akan semakin memperlambat laju korosi pada logam tersebut.

Namun disisi lain pemberian potensial negatif yang terlalu besar dapat menyebabkan terjadinya pembentukan atom-atom tunggal hidrogen yang dapat terdifusi kedalam struktur kristal logam dan menyebabkan terjadinya *hydrogen attack*. Hal ini dapat menyebabkan penggetasan pada logam.

Dasar dalam mendesain struktur adalah *safety factor* (faktor keamanan), Sehingga dalam penentuan penggunaan material, pertimbangan *material properties* seperti *yield strenght* (kekuatan tarik), *yield stress* (batas mulur), *buckling stress* (tegangan mulur) dan lainnya menjadi sangat penting. Dengan asumsi tegangan nominal pada struktur tidak melebihi tegangan *yield* maka desain struktur tersebut aman. Hal tersebut nampaknya benar dengan asumsi bahwa pada struktur tidak ada cacat (*defect*). Pada kenyataannya dalam beberapa kasus, struktur mengalami kegagalan justru pada saat beban yang diterima masih dibawah tegangan yield. Dalam perencanaan struktur dimana pelat digunakan sebagai komponen utama, struktur dapat dianggap mempunyai cacat, sehingga pendekatan *safety factor* berdasarkan *material properties* menjadi tidak valid lagi. Untuk mengatasi masalah tersebut dikembangkan konsep mekanika kepecahan yang merupakan salah satu metode matematis yang digunakan untuk mempelajari semua perilaku material termasuk adanya cacat pada material.

1.2 Tujuan

Tujuan penulisan tugas akhir ini adalah untuk mengetahui seberapa besar pengaruh pemberian potensial negatif terhadap *fracture toughness* material dalam hal ini baja SS-41. Perlakuan perlindungan korosi diberikan dengan menggunakan sel tiga elektroda dengan potensial negatif bertingkat : 0 (tidak diberi potensial), -850, -950, -1050, -1150 mV SSC. Tinjauan dilakukan dengan menganalisis data dari pengujian spesimen jenis *Compact Tension Speciment* dengan metode pengujian *plain strain fracture toughness test* dengan standard pengujian ASTM (*American Society for Testing and Material*) volume 03.01 designation: E 399-83.

Hasil dari analisis tersebut yang berupa perbandingan nilai *fracture toughness* (K_{Ic}) dari beberapa kondisi pemberian potensial negatif diharapkan dapat memberikan masukan lebih lanjut tentang pengaruh *hydrogen attack* terhadap kekuatan material.

1.3 Manfaat

Manfaat yang diperoleh dari penulisan tugas akhir ini adalah sebagai bahan referensi dalam perencanaan, pembangunan dan pengoperasian konstruksi baja yang menggunakan baja SS-41 sebagai material dasarnya serta perlindungan katodik metode ICCP (*impressed current cathodic protection*) sebagai upaya untuk memperlambat laju korosi.

1.4 Batasan Masalah

Batasan masalah pada tugas akhir ini adalah sebagai berikut :

1. Baja yang digunakan adalah baja SS-41 yang tidak diberi lapisan pelindung (*coating*)
2. Pengaruh perubahan suhu diabaikan, dalam hal ini temperatur pengujian dianggap temperatur ruang.
3. Pengaruh aliran elektrolit diabaikan.
4. Salinitas air yang dipakai dalam pengujian adalah 30.
5. Perubahan struktur kristal logam dan jarak antar elektroda tidak dibahas secara mendalam.
6. Kondisi pengujian elektrokimia sel tiga elektroda adalah dengan pemberian potensial negatif sebesar 0 (tidak diberi potensial) , –850, -950, -1050, -1150 mV SSC.
7. Jumlah spesimen uji untuk tiap kondisi adalah dua buah.
8. Tegangan sisa akibat proses mekanis pada waktu pembentukan spesimen uji diabaikan.
9. Spesimen secara umum berada dalam kondisi *plane strain*, sehingga pengaruh daerah plastis yang terjadi pada ujung retak lebih kecil dari total material spesimen.
10. Kondisi keretakan adalah kondisi dominan elastis sehingga dapat digunakan konsep *Linear Elastic Fracture Mechanics* (LEFM) dan bukaan retak linear dengan laju pembebanan.

11. Dimensi struktur yang ditinjau relatif lebih besar dibandingkan retak yang ada.

1.5 Metodologi Penelitian

Untuk mendapatkan hasil analisis yang mendasari pengambilan kesimpulan mengenai pengaruh potensial negatif terhadap *fracture toughness* baja SS-41, maka disusun metodologi penelitian sebagai berikut :

1. Studi literatur mengenai korosi, perlindungan korosi dan konsep mekanika kepecahan.
2. Studi mengenai pengujian material terdiri dari uji elektrokimia sel tiga elektroda untuk pengkondisian perlindungan katodik arus terpasang, uji tarik untuk mengetahui *mechanical properties* dan uji *plain strain fracture toughness* untuk mengetahui K_{Ic} material.
3. Penentuan material yaitu *mild steel* jenis SS-41 dan penentuan standard uji yang digunakan dalam tes spesimen adalah standard ASTM *(American Society for Testing and Material)*
4. Pelaksanaan pengujian.

   Persiapan spesimen sesuai standard ASTM E 8M-85 untuk *tension test* dan *Compact Tension Specimen Test* sesuai standard ASTM Volume 03.01 designation: E 399-83.
5. Analisis data

Penyusunan data pengujian menjadi diagram skematik antara beban dan displasemen yang nantinya dapat digunakan untuk menentukan harga dari *plain strain fracture toughness* (K_{Ic})

6. Kesimpulan dan Saran.

BAB II

KOROSI

MILIK PERPUSTAKAAN
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BAB II

KOROSI

2.1 Definisi Korosi

Korosi diartikan sebagai kondisi penurunan mutu material akibat terjadinya reaksi kimia atau elektrokimia antara material dengan lingkungannya, atau kerusakan material akibat hal lain selain proses mekanis murni [Collins, 1981].

Atom-atom logam di alam terdapat dalam bentuk campuran/senyawa kimia. Dibutuhkan sejumlah energi untuk mengolah/mengubah bijih-bijih mineral menjadi logam murni atau paduannya. Energi ini tersimpan di dalam logam sebagai *internal energy*. Proses korosi mengembalikan logam kembali seperti keadaannya di alam bebas sebelum diolah. Pada proses ini terjadi pertukaran energi *antara internal* energy pada material dengan *external energy/free energy* yang terdapat pada lingkungannya.

2.1.1 Dasar Teori Kimia Terjadinya Korosi

Dalam teori kimia, korosi terjadi akibat adanya reaksi reduksi-oksidasi (redoks) antara material dengan lingkungannya. Media utama korosi adalah air (H_2O) yang merupakan molekul netral dan bersifat *reversible*, dimana kedua jenis atom yang terkandung didalam molekul air sewaktu-waktu dapat berubah menjadi atam-atom semula. Atom uraian ini dapat menjadi sebab terjadinya korosi.

$$H_2O \Leftrightarrow H^+ + OH^-$$

Sebagai contoh adalah proses korosi pada baja di udara terbuka atau yang tercelup dalam air. Terjadinya korosi pada baja yang dicelupkan dalam air dikarenakan atom-atom logam mengalami pelepasan elektron sehingga terbentuk ion logam.

$$Fe \rightarrow Fe^{2+} + 2e^-$$

Reaksi ini dinamakan reaksi anodik atau oksidasi. Sedangkan apabila baja tersebut berada pada udara terbuka yang mengandung uap air maka udara dengan air akan mengalami reaksi katodik yang disebut reduksi oksigen seperti dibawah ini:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Dalam larutan asam, reaksi reduksinya adalah evolusi hidrogen:

$$H^+ + e^- \rightarrow H$$

$$H + H \rightarrow H_2$$

Pada baja-baja yang tercelup dalam air laut, ion-ion Cl^- dan Na^+ tidak ikut bereaksi, sebagai hasil adalah penggabungan antara reaksi anodik dan katodik sebagai berikut:

$$2Fe + 2H_2O + O_2 \rightarrow 2Fe^{2+} + 4OH^- \rightarrow 2Fe(OH)_2$$

Senyawa hasil reaksi diatas disebut senyawa karat atau garam ferro. Kondisi ini menurut teori kimia tidak akan stabil jika terus menerus berada di udara terbuka atau di air laut. Senyawa ini akan bereaksi lebih lanjut membentuk garam ferrit yaitu:

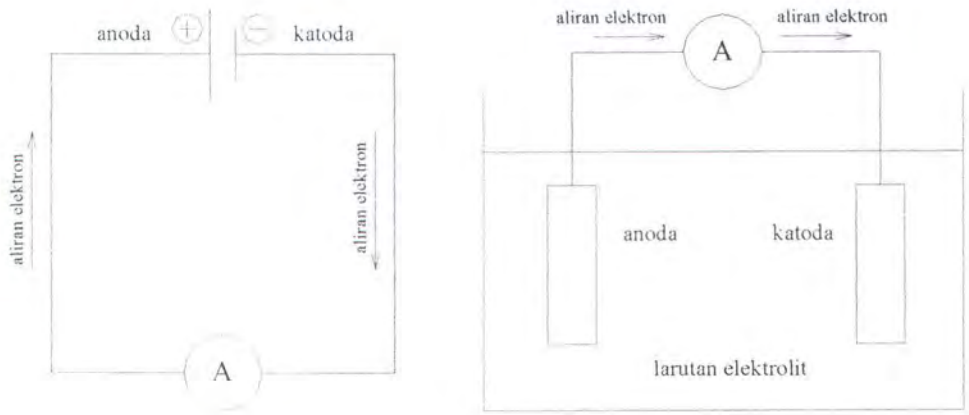
$$2Fe(OH)_2 + 2H_2O + O_2 \rightarrow 2Fe(OH)_3$$

Dari reaksi diatas dapat ditarik kesimpulan bahwa jika baja mengalami korosi maka akan berlanjut hingga habis.

2.1.2 Dasar Teori Listrik Terjadinya Korosi

Semua material mempunyai muatan listrik statis yang besarnya bervariasi. Bila dua benda dengan muatan listrik statis yang berbeda dihubungkan secara elektris (dicelupkan kedalam larutan elektrolit dan dihubungkan dengan konduktor), maka akan terjadi aliran listrik dan aliran elektron.

Pada sel batere, kutub positip disebut anoda dan kutub negatip disebut katoda. Kebalikannya dalam sel korosi, kutub positip disebut katoda dan kutub negatip disebut anoda.



Sel batere Sel korosi

Gambar 2.1 Sel batere & sel korosi

2.2 Teori Elektrokimia pada Proses Korosi

2.2.1 Reaksi Elektrokimia

Reaksi elektrokimia adalah reaksi yang melibatkan arus elektron/arus listrik, atau reaksi yang didalamnya terdapat reaksi reduksi dan oksidasi. Hampir seluruh proses korosi yang terjadi pada logam melibatkan perpindahan elektron.

Contoh reaksi elektrokimia adalah reaksi antara zinc dan hydrochloric acid yang ditunjukkan pada reaksi lengkap berikut:

$$Zn + 2HCl \rightarrow ZnCl_2 + H_2$$

Zinc bereaksi dengan larutan asam membentuk zinc chloride serta membebaskan gelembung-gelembung gas hydrogen pada permukaan. Bentuk reaksi ioniknya adalah :

$$Zn + 2H^+ + 2Cl^- \rightarrow Zn^{2+} + 2Cl^- + H_2$$

Setelah menghilangkan Cl^- dari kedua sisi reaksi, diperoleh :

$$Zn + 2H^+ \rightarrow Zn^{2+} + H_2$$

Bila diuraikan, reaksi diatas terdiri atas :

$$Zn \rightarrow Zn^{2+} + 2e^- \quad \text{reaksi anodik} \qquad [2.1]$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{reaksi katodik} \qquad [2.2]$$

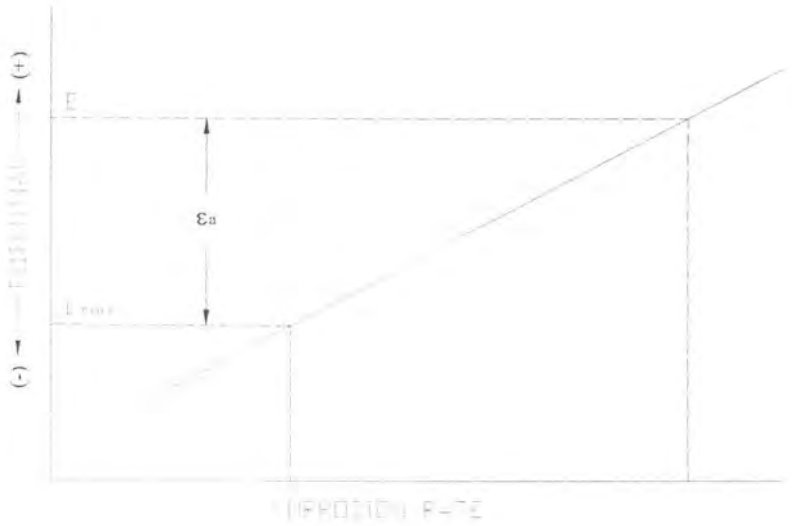
Pada reaksi anodik [2.1] valensi Zn meningkat dari 0 menjadi +2 dengan melepaskan elektron, reaksi ini disebut juga reaksi oksidasi. Sedangkan pada reaksi katodik [2.2] bilangan oksidasi hydrogen turun dari +1 menjadi 0 dengan mengkonsumsi elektron, reaksi ini disebut juga reaksi reduksi.

2.2.2 Polarisasi

Proses reaksi elektrokimia seperti [2.1] dan [2.2] terjadi dalam kecepatan reaksi yang terbatas. Jika elektron yang terbentuk untuk dipakai pada reaksi [2] banyak, potensial pada permukaaan menjadi semakin negatip, hal ini menyebabkan sisa elektron yang terkumpul pada logam atau permukaan larutan menunggu untuk bereaksi. Karena itu kecepatan reaksi tidak cukup untuk

mengakomodasi seluruh elektron yang ada. Perubahan potensial negatip ini disebut *cathodic polarization*. Demikian pula kekurangan elektron pada logam dari reaksi [2.1] menghasilkan perubahan potensial yang lebih positip, Perubahan potensial positip ini disebut *anodic polarization*. *Anodic polarization* menunjukkan gaya gerak korosi dengan terjadinya reaksi anodik.

Pada larutan elektrolit, bidang batas (permukaan logam dengan media) akan mencari *steady state potential*, E_{corr} , yang tergantung pada kemampuan dan kecepatan reaksi redoks dalam melepaskan dan memakai elektron.



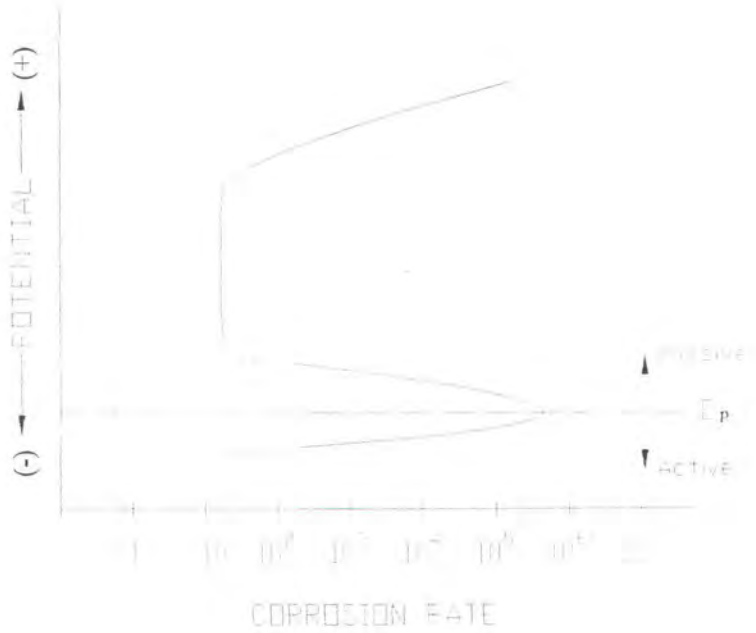
Gambar 2.2 Skema kenaikan laju korosi dengan kenaikan potensial E dan *anodic polarization* ε_a.

Ketika potensial permukaan naik diatas E_{corr} menjadi E, secara umum laju korosi akan meningkat.seperti yang ditunjukkan pada gambar 2.2 anodic polarization didefinisikan sebagai $\varepsilon a = E - E_{corr}$. Tanpa adanya polarisasi, gaya gerak korosi yang sangat kecil akan menghasilkan laju korosi yang sangat tinggi.

2.2.3 Pasivitas

Logam yang berada pada media oksidator yang kadar oksidatornya terus meningkat (potensial semakin positip), laju korosi menurun drastis setelah potensial kritis Ep, yang kemudian pada potensial tertentu kecepatan korosi stabil. Kondisi ini disebut sebagai pasivitas. Pasivitas terjadi karena terbentuknya lapisan tipis karat pelindung yang menghambat terjadinya reaksi anodik.

Selain keuntungan akibat penurunan laju korosi , permasalahan yang timbul dari pasivitas ini adalah karena sifatnya yang tipis dan mudah pecah. Rusaknya lapisan ini menghasilkan korosi lokal sulit diprediksi seperti korosi celah, korosi lubang, korosi celah dan korosi tegangan.



Gambar 2.3 Pasivitas pada potensial oksidasi diatas Ep

2.3 Faktor-faktor yang Berpengaruh Terhadap Korosi

2.3.1 Faktor Penyebab Korosi

Setiap logam maupun paduannya bila tercampur dan bereaksi dalam suatu lingkungan korosif akan mengalami korosi. Faktor-faktor yang mempengaruhi terjadinya korosi pada logam-logam atau paduannya adalah sebagai berikut:

1. Struktur material

   Homogenitas struktur suatu material ditentukan oleh susunan kimia, perlakuan panas dan perlakuan mekanis dari material. Bila struktur mikro material tersebut kurang atau tidak homogen, akan terjadi apa yang dinamakan dengan sel korosi mikro galvanis. Pekerjaan mekanis dapat menyebabkan butiran dalam material mengalami perubahan bentuk dan susunannya, sehingga apabila logam berada dalam larutan elektrolit akan terjadi aliran listrik karena sebagian kristal akan menjadi katoda bagi kristal lainnya.

2. Deformasi plastis dan elastis.

   Hampir semua logam dalam pembuatannya terdeformasi, akibatnya permukaan logam mempunyai struktur yang sifatnya berbeda. Adanya struktur kristal permukaan yang berbeda menyebabkan terjadinya korosi.

3. Bentuk permukaan logam.

   Permukaan logam mempunyai struktur tersendiri mengenai keaktifannya membentuk lapisan oksida logam yang fungsinya menghambat pengkaratan.

4. Pengaruh beda potensial.

   Dua logam yang mempunyai beda potensial tidak sama bila digabungkan dan dimasukkan kedalam larutan elektrolit akan terjadi pengkaratan.

5. Komposisi air laut.

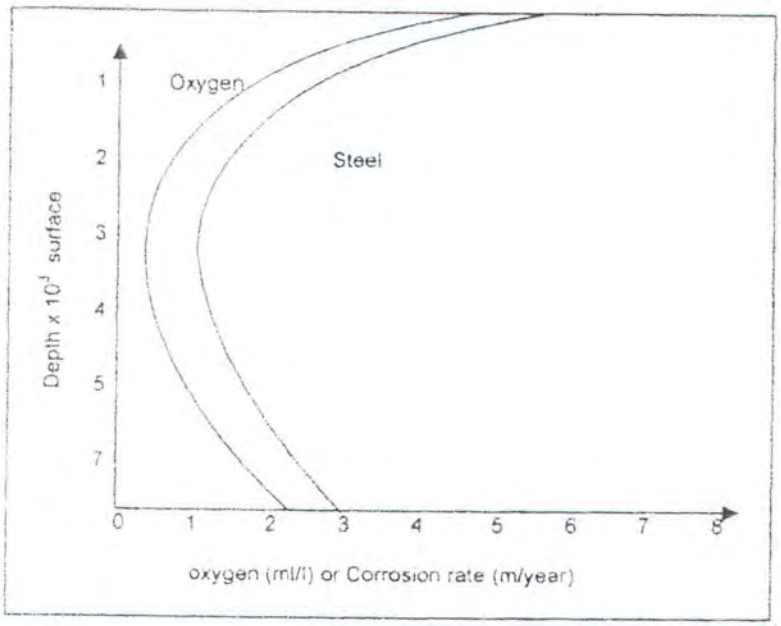
   Air laut merupakan campuran senyawa kimia dan masing-masing senyawa memiliki sifat yang berbeda-beda secara sistematik. Akibat dari sifat-sifat itu akan menyebabkan terjadinya korosi dari beberapa logam yang tercelup kedalam air laut. Di bawah ini adalah senyawa-senyawa yang terdapat dalam air laut menurut tabel 2.1. [Chandler, 1985].

Tabel 2.1. Komposisi senyawa kimia dalam air laut (g/kg)

SENYAWA	**g/kg**
Sodium	12,77
Magnesium	1,30
Kalsium	0,409
Potassium	0,338
Strontium	0,010
Chloride	19,37
Sulfat (SO_4)	2,71
Brom	0,065
Boric acid (H_3BO_3)	0,026
Total salts	**35,1**

6. Pengaruh oksigen.

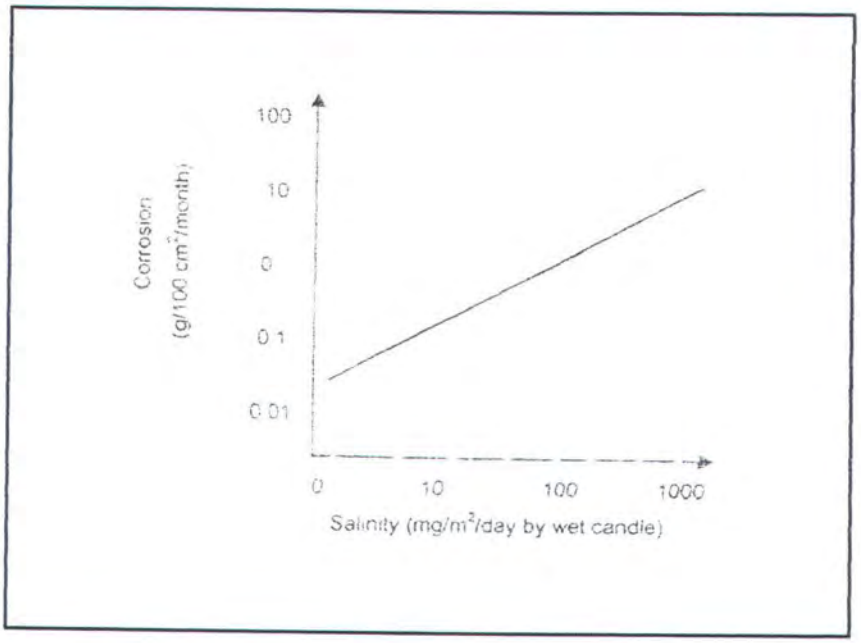
   Kandungan oksigen maksimum pada tekanan 1 atm temperatur 25^0 C adalah 10 mg O_2 per liter. Oksigen pada proses korosi dapat membentuk lapisan pelindung oksida pada permukaan logam yang menimbulkan sifat pasivitas pada logam tersebut.



Gambar 2.4. Hubungan antara kandungan oksigen dan laju korosi dari besi dengan kedalaman air laut. [Laque, 1975].

7. Salinitas.

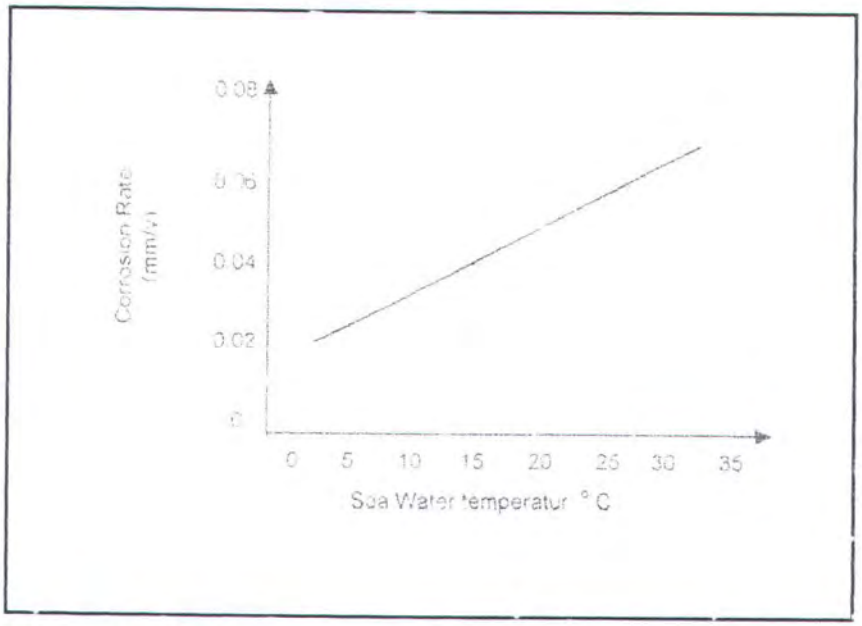
Total kandungan garam yang terdapat dalam air laut disebut salinitas yang didefinisikan sebagai banyaknya kadar garam dalam gram per liter. Untuk berbagai wilayah perairan dunia salinitas berkisar antara 32 sampai 38, sedang perairan Indonesia berkisar antara 30 sampai 35. Salinitas sangat berpengaruh terhadap laju korosi, semakin tinggi salinitas maka semakin cepat laju korosi seperti tampak dalam gambar 2.3 [Laque, 1975].



Gambar 2.5. Hubungan antara salinitas dengan laju korosi dari mild steel.

8. Temperatur.

Semakin tinggi temperatur maka laju korosi akan semakin cepat, seperti tampak dalam gambar 2.4 [Laque, 1975].



Gambar 2.6 Pengaruh temperatur terhadap korosi besi dalam air laut.

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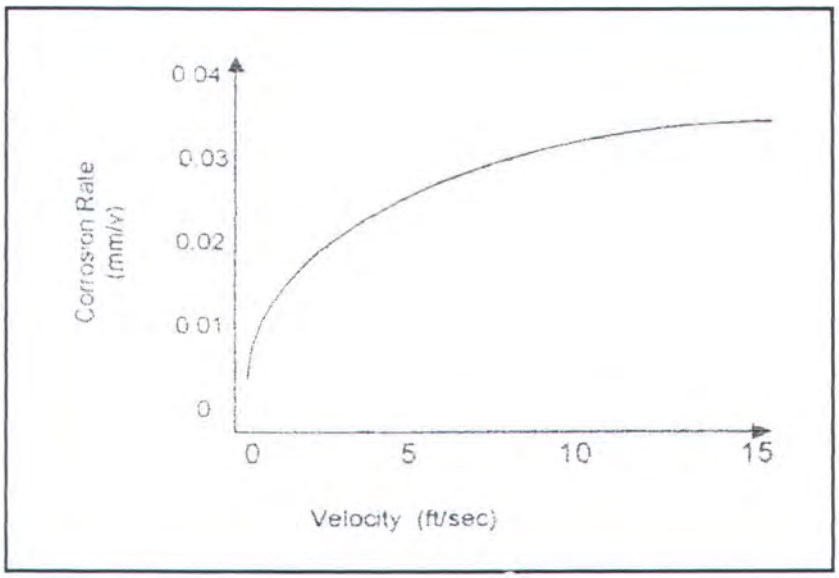
9. Kecepatan

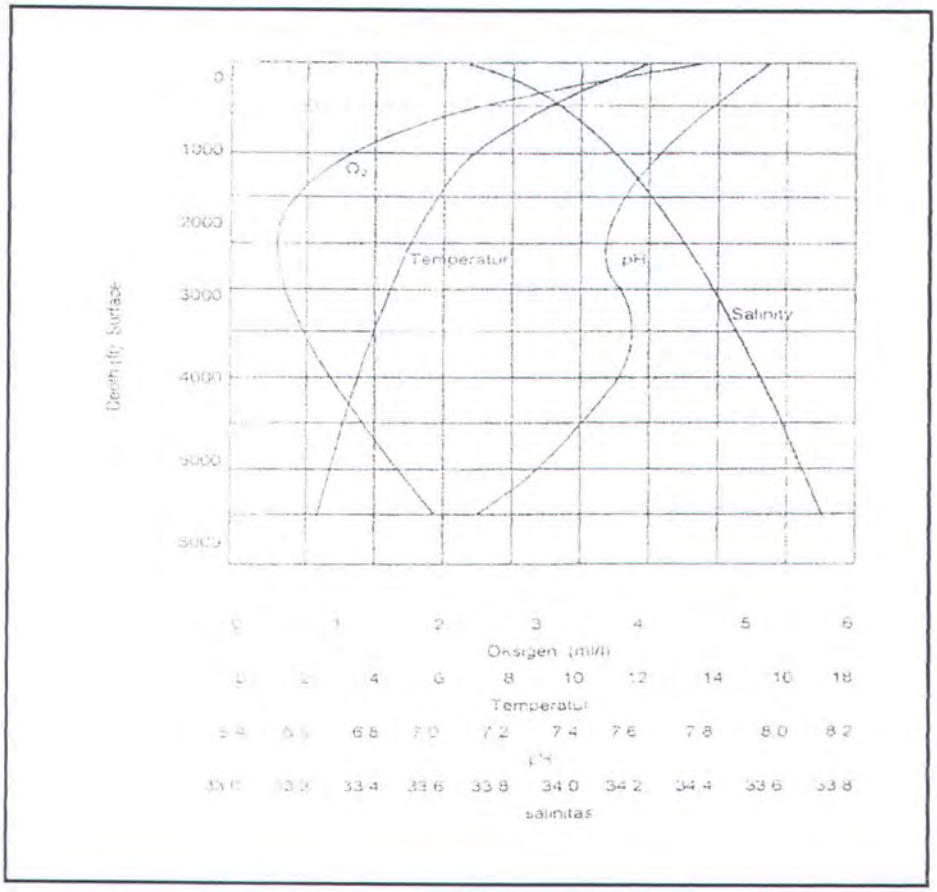
Kecepatan gerakan air laut sangat berpengaruh terhadap laju korosi logam, hal ini sebagai akibat pengaruh pertambahan reaksi oksigen di permukaan logam. Semakin tinggi kecepatan aliran, maka laju korosi semakin cepat. Hal ini ditunjukkan dalam gambar 2.5 [Laque, 1975].



Gambar 2.7 Pengaruh kecepatan aliran air laut terhadap laju korosi besi.

10. Unsur-unsur halogen.

Unsur Cl, Br dan I dalam suatu media korosi akan menyebabkan rusaknya pasivitas suatu material atau ketahanan pengkaratan akan hilang. Dengan adanya hasil reaksi antara logam dengan unsur-unsur halogen tersebut, akan mempercepat terjadinya korosi.



Gambar 2.8. Hubungan antara kedalaman dengan temperatur, kandungan oksigen, pH dan salinitas menurut F. L. L Laboratory at Harbor Island, North Carolina [Laque, 1975].

2.3.2 Pengaruh Lingkungan terhadap Korosi

Lingkungan yang menyebabkan kerusakan pada material disebut lingkungan korosif yang terbagi dalam beberapa bagian [Fontana, 1986]:

1. Lingkungan udara beruap air dan air yang mengandung mineral.
2. Polutan industri yang terdiri dari uap air, gas-gas seperti amoniak, hidrogen sulfida, klorin, asam-asam organik.
3. Minyak.
4. Lingkungan bersuhu tinggi.

Pengaruh Lingkungan terhadap terjadinya korosi dapat dilihat pada beberapa kondisi sebagai berikut [Collins, 1981] :

1. Udara terbuka

   Fartor-faktor yang paling berpengaruh pada kondisi udara terbuka adalah temperatur, waktu basah (*time-of-wetness*), serta jenis dan jumlah unsur kimia yang mengotori.

2. Air

   Pada perairan alam dan lingkungan berair lainnya, korosi pada baja dipengaruhi oleh konsentrasi oksigen terlarut, temparatur, kesasaman, garam terlarut dan kecepatan aliran..

3. Tanah

   Korosi pada baja yang terpendam dalam tanah sebagian besar ditentukan oleh kelembaban tanah, konduktifitas yang dipengaruhi oleh garam terlarut, tingkat aerasi serta keasamam tanah. Ada juga yang dipengaruhi oleh bakteri. Pada kondisi anaerob, bakteri sulfat dapat membentuk hidrogen sulfida yang dapat merusak baja.

4. Temparatur tinggi

   Pada temparatur tinggi diatas 220 °C, lingkungan yang mengandung hidrogen dapat menyebabkan kerusakan yang parah pada baja karbon. Hidrogen terdifusi kedalam baja dan bereaksi dengan *iron carbides* membentuk *methane*. Tekanan tinggi didalam baja dapat meyebabkan kegagalan retak. Penambahan unsur-unsur pada logam paduan seperti

chromium, molybden, titanium, dan vanadium dapat secara efektif menghambat terjadinya pengrusakan oleh hidrogen.

2.4 Jenis-jenis Korosi

Jenis-jenis korosi bisa bermacam-macam yang tergantung dari banyak faktor seperti jenis material, kondisi lingkungan, proses pembentukan atau fabrikasi material dan sebagainya. Untuk mempermudah membedakan macam korosi yang terjadi, berikut ini diklasifikasikan secara garis besar jenis-jenis korosi:

1. Korosi homogen *(uniform: corrosion)*

   Jenis korosi yang sering dan umum terjadi pada konstruksi logam. Korosi jenis ini mengakibatkan pengkaratan pada seluruh bagian material yang terekspose dalam atmosfir. Korosi homogen biasanya mudah diprediksi dan diukur, dimana berkurangnya ketebalan logam merupakan fungsi waktu.

   Misal: baja yang terekspose dalam atmosfir yang lembab.

$$\begin{array}{rcll} Fe & \rightarrow & Fe^{2+} + 2e & \} \times 2 \\ O_2 + 2H_2O + 4e & \rightarrow & 4OH^- & + \\ \hline 2Fe + O_2 + 2H_2O & \rightarrow & 2Fe^{2+} + 4OH^- & \\ 2Fe + O_2 + 2H_2O & \rightarrow & 2Fe(OH)_2 & \end{array}$$

   Proses korosi logam besi dalam air menghasilkan karat besi $2Fe(OH)_2$ yang berwarna coklat dan menyebabkan menipisnya permukaan besi.

2. Korosi galvanis *(galvanic corrosion)*

   Terjadi karena adanya perbedaan potensial antara dua logam atau lebih yang digabungkan dalam suatu elektrolit. Logam yang mempunyai potensial rendah atau tahanan korosi rendah akan terkikis, dan yang potensialnya lebih tinggi atau tahanan korosinya tinggi mengalami penurunan tahanan korosinya. Logam yang tahanan korosinya kecil disebut anodik dan menjadi logam aktif, sebaliknya logam yang tahanan korosinya tinggi bersifat katodik dan menjadi logam pasif. Proses korosi diawali dengan mengalirnya elektron diantara dua logam. Semakin besar beda potensial antara dua logam dalam larutan elektrolit akan semakin cepat pula aliran elektron yang terjadi dan laju korosi akan semakin cepat.

3. Korosi lubang *(pitting corrosion)*

   Merupakan bentuk pengkaratan yang terpusat pada satu titik dengan kedalaman tertentu. Serangan yang kecil dan dalam akan sulit untuk dideteksi. Banyak logam yang terkorosi relatif kecil dibanding berat logam seluruhnya. Proses korosi berjalan cepat dan bentuk mengarah ke arah gravitasi.

4. Korosi celah *(crevice corrosion)*

   Sering menyerang pada celah dan permukaan tertutup lainnya dari suatu logam yang terletak dalam media korosif. Perusakan korosi selalu dalam skala kecil dari larutan yang terperangkap lewat lubang, kotoran permukaan logam, baut atau kepala keling dan celah dibawah mur. Korosi ini disebut juga korosi deposit atau *gasket corrosion*, dan merupakan

korosi lokal dengan serangan hebat dan sulit terdeteksi karena tidak tampak dari luar. Celah logam pada media korosi bersifat anodik akan terkena korosi, sedangkan bagian logam lainnya bertindak sebagai katodanya.

5. Korosi tegangan *(stress corrosion)*

   Korosi ini muncul saat material mendapat perlakuan pembentukan baik *cutting* maupun *bending*. Karena perlakuan tersebut maka akan muncul perbedaan tegangan yang mengakibatkan terjadinya aliran elektron dalam material dan meyebabkan terjadinya korosi pada bagian material yang mendapat perlakuan cutting dan bending tersebut.

6. Korosi lelah *(fatique corrosion)*

   Terjadi pada tegangan dibawah *yield point* akibat adanya pembebanan cyclic. Retak merambat sampai luas penampang melintang dari logam berkurang sampai pada suatu titik dimana *ultimate strength* dilalui hingga *brittle fracture* terjadi secara cepat. Korosi ini didefinisikan sebagai penurunan ketahanan *fatique* akibat adanya media yang bersifat korosif.

7. Korosi batas butir *(intergranular corrosion)*

   Terjadi pada daerah batas butir *(grain boundary)* akibat adanya kekosongan unsur atau elemen pada kristal logam setelah mengalami proses pembentukan. Korosi ini sulit diamati dengan mata telanjang karena tidak terjadi di permukaan logam melainkan pada butiran kristal. Terkadang tanpa ada perubahan pada kristalnya baik secara kuantitatif maupun geometri. Serangan pada butir atau batas butir menyebabkan

perubahan susunan kristal logam yang berakibat renggangnya ikatan antara kristal. Hal ini akan mempengaruhi sifat ketangguhan *(toughness)* atau kekerasan *(hardness)* material.

8. Korosi erosi

Disebabkan karena adanya gerakan relatif antara fluida korosif dengan permukaan logam. Korosi ini mengakibatkan terkikisnya lapisan film pada permukaan logam yang berfungsi sebagai pelindung logam dari serangan korosi. Penambahan kecepatan gerakan relatif antara logam dengan media korosif mengakibatkan bertambahnya pengikisan lapisan pelindung logam.

9. Hydrogen Damage

Hydrogen damage merupakan suatu kerusakan yang diakibatkan oleh atom tunggal hidrogen. Karena ukurannya yang sangat kecil sehingga atom ini dapat berdifusi ke dalam sebuah logam. Ada empat jenis *hydrogen damage*:

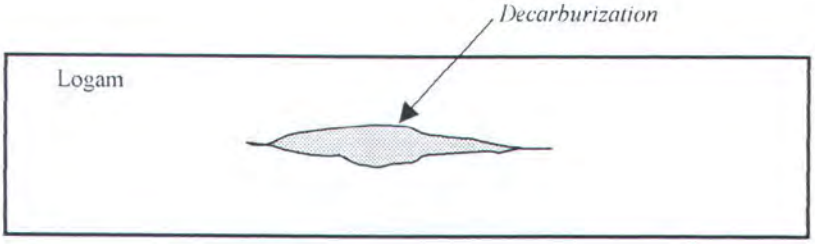
a. *Decarburization* dan *Hydrogen Attack*

Decarburization dan *hydrogen attack* terjadi apabila logam berada pada lingkungan yang mengandung hidrogen bertekanan tinggi dalam waktu yang lama. Atom-atom karbon dan hidrogen dalam logam akan bereakasi.

$$F_eC + 2H_2 \rightleftharpoons CH_4 + F_e$$

Pada suhu 470 ^{0}C reaksi tersebut diatas berada pada posisi setimbang namun pada suhu yang lebih rendah reaksi akan cenderung ke arah kanan

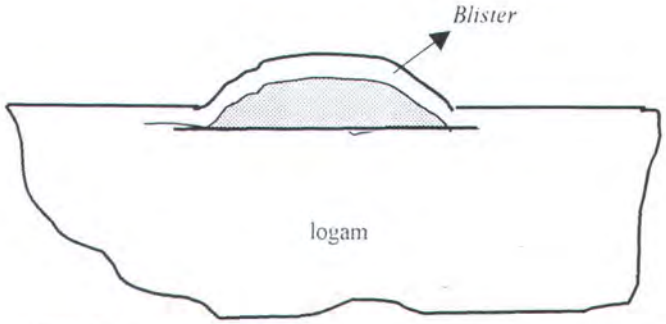
dan membentuk metan. Gas metan yang terbentuk didalam logam tidak dapat menyeruak keluar. Jika gas metan terkumpul dan menumpuk di daerah cacat pada logam maka tekanan di daerah tersebut akan meningkat. Tekanan yang tinggi ini akan dapat mengakibatkan terjadinya gelembung dan peretakan di daerah tersebut. Jika reaksi tersebut di atas terjadi pada suhu yang tinggi maka reaksi akan cenderung ke arah kiri dan membentuk gas hidrogen. Akibat pembentukan gas hidrogen di dalam logam pada suhu yang tinggi akan dapat mengakibatkan peretakan.



Gambar 2.9. Kerusakan material akibat proses *decarburization.*

b. Hidrogen Blistering

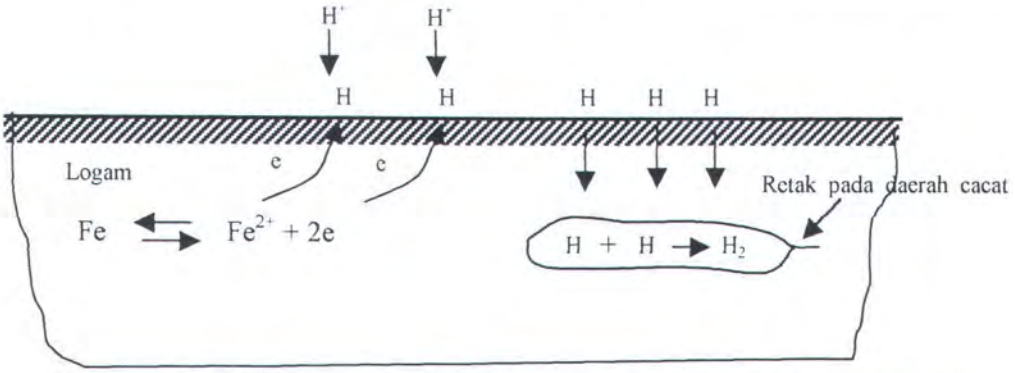
Hidrogen blistering terjadi akibat difusi atom tunggal hidrogen di daerah cacat pada logam yang terletak di dekat permukaan. Atom hidrogen yang terperangkap di daerah cacat akan berevolusi membentuk gas hidrogen. Gas hidrogen yang terkumpul makin lama makin banyak sehingga tekanan di daerah cacat akan meningkat. Karena besarnya tekannan yang terjadi maka di daerah cacat tersebut akan terjadi gelembung (*blister*) seperti gambar berikut :



Gambar 2.10. Kerusakan logam akibat *hydrogen blistering*.

c. *Hydrogen Embritlement*

Proses yang terjadi pada *hydrogen embritlement* hampir sama dengan *hydrogen blistering*. Tekanan yang tinggi akibat gas hidrogen yang terkumpul di daerah cacat yang berada jauh dari permukaan logam akan dapat mengakibatkan peretakan dan perapuhan di daerah cacat tersebut.



Gambar 2.11. Skematik difusi atom tunggal hidrogen ke dalam sebuah logam [Jones, 1992]

10. Korosi biologi

Diakibatkan secara langsung maupun tidak langsung dari aktifitas organisme hidup seperti ganggang atau bakteri. Aktifitas organisme hidup menimbulkan korosi dengan cara mempengaruhi secara langsung terhadap reaksi anodik dan katodik, lapisan pelindung dan menciptakan kondisi korosif.

2.5. Pengendalian Korosi

Proses korosi tidak dapat dihilangkan, namun hanya dapat dikendalikan sehingga umur dari struktur atau komponen menjadi lebih lama. Setiap komponen mengalami tiga tahapan utama dalam suatu pembentukan struktur yaitu perancangan, pembuatan dan pemakaian. Pengendalian korosi memainkan peranan penting dalam tiap tahapan tadi, ketidakberhasilan salah satu dari aspek-aspek pengendalian korosi ini bisa menyebabkan komponen mengalami kegagalan prematur.

Pengendalian korosi bisa dilakukan dengan berbagai macam cara, tetapi yang paling utama dilakukan dalam usaha pengendalian korosi adalah [Trethewey dan Chamberlain, 1991]:

- Modifikasi disain
- Modifikasi lingkungan
- Pemberian lapisan pelindung
- Pemilihan bahan
- Perlindungan katodik atau anodik

Untuk proses pengendalian korosi yang terjadi pada bangunan kapal, khususnya dibawah garis air, sering dilakukan dengan cara:

- Pemberian lapisan pelindung *(Coating)*

  Pemberian lapisan pelindung pada permukaan logam berfungsi untuk memisahkan lingkungan korosif dengan logam dan mengendalikan lingkungan mikro pada permukaan logam. Cara pelapisan yang digunakan misalnya cat, selaput organik, vernis, lapisan logam dan enamel.

- Anoda tumbal *(sacrificial anodes)*

  Pengendalian korosi dengan cara mengorbankan logam yang bersifat anodik untuk melindungi logam katoda yang merupakan bahan logam utama konstruksi. Dalam hal ini, logam yang ditumbalkan harus mempunyai potensial yang lebih rendah dari logam utama sehingga yang terkorosi adalah logam tambahan, dan logam utama terhindar dari korosi.

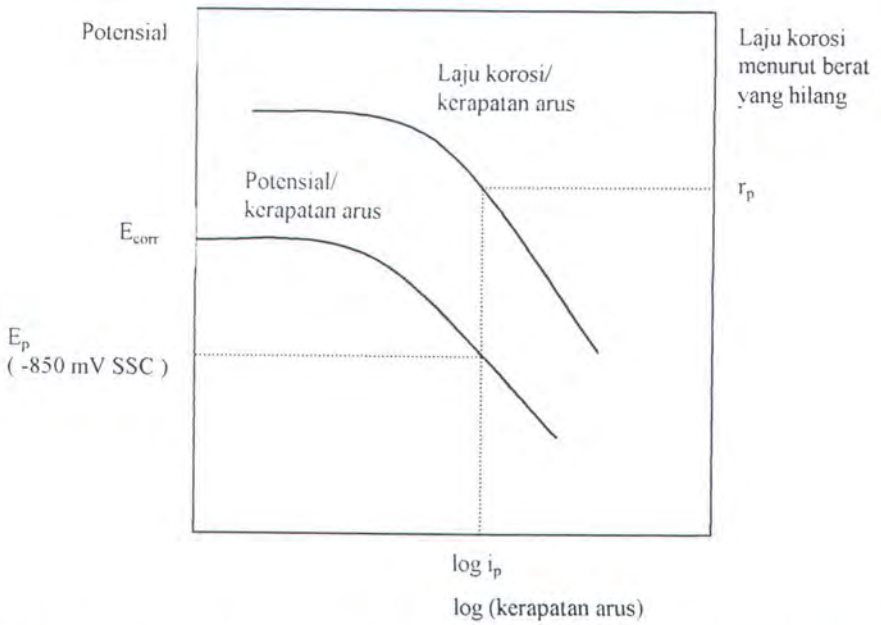
- Pemberian potensial perlindungan katodik *(impressed current)*

  Pengendalian korosi ini dilakukan dengan cara memasok sejumlah arus yang dibutuhkan oleh suatu konstruksi. Anoda yang digunakan dalam sistem ini dapat berupa anoda termakan atau permanen. Logam yang mempunyai kerapatan arus tinggi apabila digunakan sebagai anoda harus dikelilingi dengan lapisan pelindung arus *(protective shields)*. Lapisan pelindung ini dimaksudkan untuk menghindari terlalu tingginya kerapatan arus katoda di sekitar anoda. Pengendalian ini dilengkapi dengan transformator dan sistem pengendali untuk mengatur jumlah kebutuhan arus listrik pada konstruksi.

2.6 Potensial Perlindungan Katodik

Suatu material akan mengalami pengkaratan bila material tersebut bertidak sebagai anoda dalam sel galvanis, sedangkan material yang bertindak sebagai katoda tidak akan mengalami pengkaratan. Dengan dasar tersebut pencegahan pengkaratan dapat dilakukan dengan cara memberikan atau mengalirkan potensial negatif pada logam. Cara pencegahan seperti ini disebut sebagai pencegahan

pengkaratan dengan menggunakan perlindungan katodik *(impressed current cathodic protection)*. Semakin negatif potensial yang diberikan pada material maka reaksi anodik yang terjadi akan semakin lambat namun sebaliknya reaksi katodik menjadi lebih cepat sehingga logam menjadi lebih katodik. Dengan lambatnya reaksi anodik maka laju korosi yang terjadi semakin lambat pula. Hal tersebut ditunjukkan dalam gambar 2.12:



Gambar 2.12. Variasi potensial katodik terhadap kerapatan arus untuk baja dalam air laut serta hubungannya dengan laju korosi yang diukur dari berat yang hilang [Trethewey dan Chamberlain, 1988].

Gambar tersebut memperlihatkan korosi yang dialami oleh logam semakin sedikit bila potensial dibuat lebih negatif [Trethewey dan Chamberlain, 1991]. E_{corr} merupakan potensial dimana logam mengalami korosi. Pada kondisi ini kerapatan arus yang dihasilkan kecil dan laju korosi yang dihitung dari berat yang hilang besar. E_P –850 mV SSC adalah potensial perlindungan katodik yang

diberikan pada logam, dimana pada kondisi ini kerapatan arus yang terjadi menjadi lebih besar dan korosi yang dialami logam semakin sedikit.

Dengan demikian pencegahan pengkaratan pada suatu konstruksi dapat dilakukan dengan jalan membuat material konstruksi bertindak sebagai katode. Langkah yang harus dilakukan untuk memenuhi hal tersebut adalah dengan mengalirkan arus potensial negatif kepada material. Perlindungan katodik memerlukan jumlah arus yang sesuai agar dapat berfungsi dengan baik. Ada beberapa faktor yang mempengaruhi besarnya kerapatan arus, faktor-faktor tersebut adalah:

a. Luas permukaan material.

   Lebih besar permukaan material yang berhubungan dengan air laut, maka semakin besar pula elektron yang harus diterima oleh permukaan material tersebut.

b. Kecepatan aliran.

   Bertambah besarnya kecepatan aliran fluida maka akan memperbesar kepadatan arus yang diperlukan. Dengan bertambah cepatnya aliran air laut maka memungkinkan oksigen yang mencapai permukaan material semakin banyak.

c. Temperatur air laut.

   Temperatur air laut berbeda untuk daerah perairan satu dengan lainnya. Kenaikan temperatur akan menyebabkan semakin besarnya oksigen yang mencapai permukaan logam. Kenaikan oksigen ini akan menyebabkan bertambah besarnya kepadatan arus yang dibutuhkan.

Seperti yang telah disebutkan diatas bahwa reaksi anodik yaitu proses berubahnya logam menjadi ion logam menjadi lebih lambat, tetapi reaksi katodik semakin cepat bila potensial perlindungan katodik yang diberikan semakin negatif *(cathodic overprotection)*. Dengan semakin cepatnya reaksi katodik ini akan mempercepat pula terjadinya evolusi hidrogen, yaitu proses pembentukan gas hidrogen:

$$H^+ + e \longrightarrow H$$

$$H + H \longrightarrow H_2$$

Atom hidrogen hanya memiliki satu proton dalam intinya, sehingga atom hidrogen sangat kecil, hal tersebut menyebabkan atom hidrogen dengan cepat berpindah melalui struktur kristal logam [Jones, 1992]. Jadi, penggunaan perlindungan katodik yang semakin negatif selain mampu memperlambat proses pengkaratan juga dapat menyebabkan terjadinya difusi atom hidrogen kedalam logam. Dengan meningkatnya konsentrasi hidrogen dalam logam maka kecenderungan terjadinya penggetasan *(embrittlement)* pada logam juga semakin meningkat [Fontana, 1986]. Penggetasan yang disebabkan karena konsentrasi hydrogen dalam logam dikenal sebagai *hydrogen embrittlement.* Penggetasan ini, akan dapat mengurangi kekuatan logam.

2.7 Karakteristik Hydrogen dalam Material

Aspek-aspek yang mendasari permasalahan yang ditimbulkan oleh keberadaan hydrogen dalam material meliputi :

- Kemampularutan hydrogen dalam kisi-kisi molekul (struktur material) yang tidak tinggi.
- Kecenderungan yang tinggi untuk terserap kedalam atau keluar melalui permukaan material.
- Terserapnya hydrogen kedalam kisi dan perpindahannya oleh proses difusi, pergerakan cacat serta pengumpulan hydrogen pada bagian dalam *bulk metal*.

Meskipun kemampularutan hydrogen tidaklah tinggi, hydrogen mudah berinteraksi dengan material melalui berbagai cara seperti :

- *Precipitation*
- *Inclusion*
- *Grain boundaries* (batas butir)
- Reaksi dengan elemen tertentu membentuk *hydrides*

Interaksi ini seringkali membutuhkan perpindahan hydrogen diantara *bulk metal*, dan mobilitas yang tinggi berperan dalam sifat merusak pada baja. Ukuran molekul hydrogen relatif besar dan hanya bentuk atom hydrogen yang lebih kecil yang dapat terdifusi secara efektif. Jadi larutan dengan kandungan ion hydrogen dapat menjadi sumber pengisi baja dengan hydrogen yang terdifusi melalui *bulk metal*.

Hydrogen yang terdapat pada baja pada temperatur ruang, dapat menyebabkan turunnya *ductility*, terjadinya *blistering, step-wise cracking* atau *delayed cracking*, dimana kelanjutan retak terjadi pada tegangan yang jauh

dibawah dari yang seharusnya dibutuhkan untuk terjadinya pertambahan retak pada kondisi tanpa kehadiran hydrogen [Collins, 1981].

BAB III

FRACTURE MECHANICS

BAB III

FRACTURE MECHANICS

3.1 Prinsip Dasar *Fracture Mechanics*

3.1.1 Pendahuluan

Filosofi dasar desain struktur adalah proses pengambilan keputusan yang iteratif dalam perancangan dan optimasi dari teknologi baru ataupun pengembangan teknologi dalam memenuhi kebutuhan dan keinginan manusia [Collins, 1981]. Struktur yang akan dibuat atau dibangun perlu didesain sesuai dengan kondisi lingkungan dimana struktur tersebut bekerja, dengan demikian moda-moda kegagalan yang mungkin dapat terjadi bisa diprediksi dan dihindari.

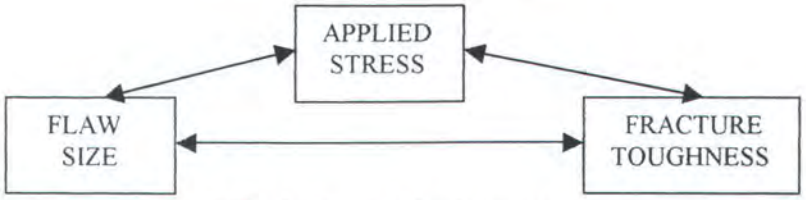
Penyebab terjadinya kegagalan struktur dalam banyak konstruksi dapat secara umum digolongkan kedalam dua kategori, yaitu:

1. Kelalaian dalam perencanaan, pembangunan atau pemakaian struktur.
2. Penerapan desain atau material baru dengan hasil yang tidak terprediksi dan tidak diinginkan.

Pada kategori pertama, penggunaan prosedur yang baik dapat menghindarkan terjadinya kegagalan pada struktur. Jenis kegagalan kedua lebih sulit dihindari. Ketika teknologi baru diperkenalkan, banyak faktor yang tidak terantisipasi oleh perancangnya. Sebagai konsekuensi dari tingginya biaya pengujian dan analisis terhadap teknologi baru, banyak pengabaian-pengabaian yang dilakukan selama pengujian dan analisis tersebut.

Perencanaan struktur harus memenuhi faktor keamanan (*safety factor*) operasional, dimana struktur harus didesain mampu menerima beban operasi yang direncanakan atau beban yang diprediksi akan bekerja pada struktur tersebut. Sehingga dalam penentuan penggunaan material, pertimbangan *material properties* seperti *yield strenght* (kekuatan tarik), *yield stress* (batas mulur), *buckling stress* (tegangan mulur) dan lainnya menjadi sangat penting. Dengan asumsi tegangan nominal pada struktur tidak melebihi tegangan *yield* maka desain struktur tersebut aman. Asumsi tersebut benar apabila pada struktur tidak terdapat cacat (*defect*). Pada kenyataannya dalam beberapa kasus, struktur mengalami kegagalan justru pada saat beban yang diterima masih dibawah tegangan *yield*. Dalam perencanaan struktur dimana pelat digunakan sebagai komponen utama, struktur dapat dianggap mempunyai cacat, sehingga pendekatan *safety factor* yang hanya berdasarkan *material properties* menjadi tidak valid lagi. Untuk mengatasi masalah tersebut digunakan konsep mekanika kepecahan yang merupakan salah satu metode matematis untuk mempelajari perilaku material termasuk adanya cacat pada material.

(a) *The strength of material approach*



(b)The fracture mechanics approach

Gambar 3.1 Perbandingan pendekatan mekanika kepecahan dan pendekatan kekuatan material

Retak merupakan bagian dari kegagalan yang terjadi pada konstruksi. Dengan adanya retak, kegagalan pada konstruksi dapat terjadi lebih cepat. Sedang kegagalan akhir, adalah merupakan proses akhir yang terjadi pada konstruksi.

3.1.2 Ketangguhan Material

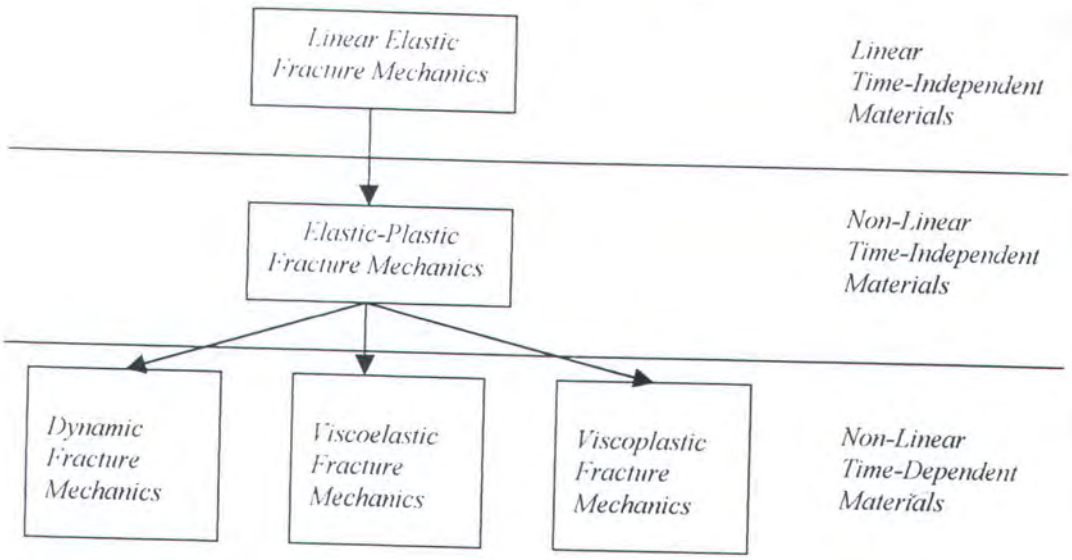
Material toughness adalah kemampuan material untuk menyerap energi dalam proses pembentukan deformasi plastis tanpa mengalami kepecahan. Dapat pula diartikan sebagai kemampuan suatu material menahan suatu beban yang dapat diuraikan melalui dua pendekatan mekanika kepecahan yaitu kriteria energi (*energy criterion*) dan faktor intensitas tegangan (*stress intensity factor*). [Anderson, 1991]

Pada pendekatan kriteria energi, kelanjutan retak terjadi bilamana energi yang bekerja bagi pertumbuhan retak tepat melebihi daya tahan material. Daya tahan material ini dapat berupa energi permukaan, gaya plastis ataupun jenis energi lain yang hilang bersama bertambahnya retak. Besarnya energi yang dilepaskan, G, yang didefinisikan sebagai besarnya perubahan energi potensial pada daerah retak untuk material linier elastis, pada saat terjadinya kepecahan nilainya sama dengan nilai kritis energi yang dilepaskan material, G_c , sebagai ukuran *fracture toughness* material, $G = G_c$.

Prinsip dasar pada mekanika kepecahan dengan pendekatan faktor intensitas tegangan (*stress intensity factor*) adalah retak yang tidak stabil terjadi bilamana faktor intensitas tegangan, K, diujung retak mencapai harga kritis, K_c , dimana K_c adalah suatu faktor yang menunjukkan kemampuan suatu bahan untuk

memikul tegangan tertentu pada ujung retak dan menghambat penjalaran retak. Maka harga K_c dapat dinyatakan sebagai *fracture toughness* atau ketangguhan retak material. Sehingga harga K_c ini dapat dipakai sabagai standard atau kriteria dalam perancangan kekuatan struktur.

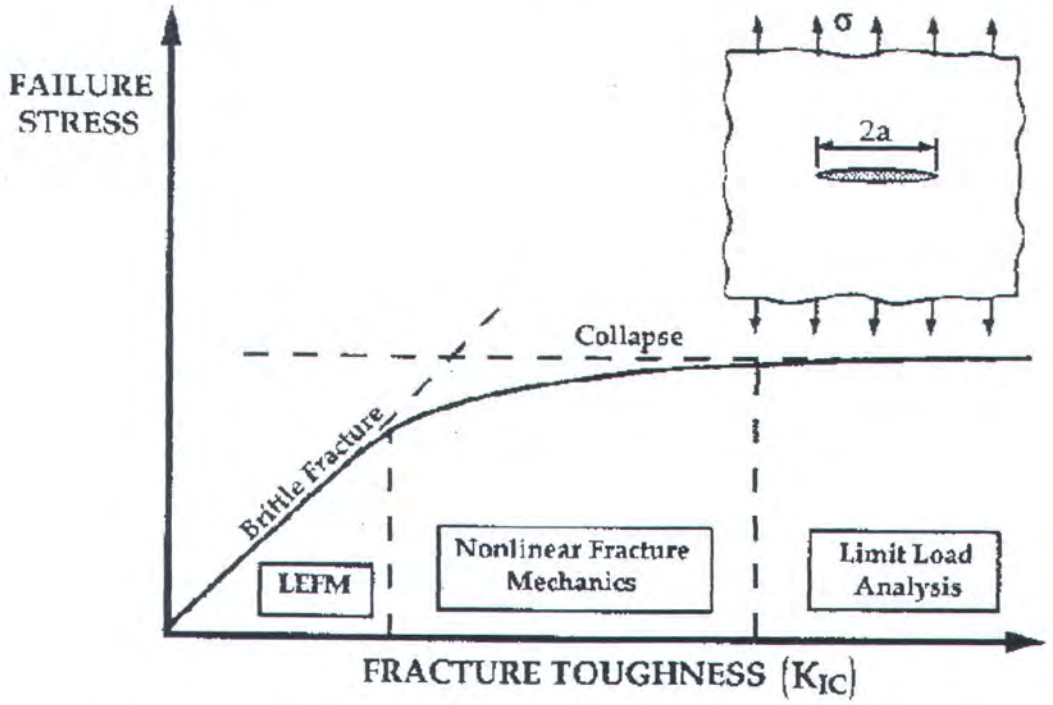
3.1.3 Pengaruh *Material Properties* pada *Fracture*



Gambar 3.2 Diagram pohon *fracture mechanics*

Gambar 3.2 menunjukkan penggolongan dalam mekanika kepecahan yang masing-masing bekerja dibawah kondisi yang berbeda. *Linear elastic fracture mechanics* digunakan untuk material dengan deformasi elastis pada kondisi *quasistatic*. *Elastic-plastic fracture mechanics* digunakan pada material dengan memperhatikan deformasi plastis pada kondisi *quasistatic*. *Dynamic, viscoelastic,* dan *viscoplastic fracture mechanics* digunakan untuk material dengan memperhatikan deformasi plastis dan variabel waktu yang berperan didalamnya.

Elastic-plastic, dynamic, viscoelastic, dan *viscoplastic fracture mechanics* digolongkan kedalam *non-linear fracture mechanics.*



Gambar 3.3 Pengaruh *fracture toughness* terhadap analisis *fracture mechanics*

Penggunaan metode analisis mekanika kepecahan berdasarkan nilai *fracture toughness* ditunjukkan pada gambar 3.3. Pada material dengan *toughness* yang rendah, brittle fracture menyebabkan terjadinya kegagalan mekanis dan tegangan kritis berubah secara linier terhadap K_{IC} . Untuk nilai *toughness* yang sangat tinggi, penggunaan LEFM menjadi tidak valid dan kegagalan lebih dipengaruhi oleh *properties* dari material karena tegangan kritis tidak lagi berpengaruh terhadap *toughness.* Pada tingkat *toughness* menengah, terjadi transisi antara *brittle fracture* dibawah kondisi *linear elastic* dan *ductile overload.*

Pada kondisi inilah *non-linear fracture mechanics* digunakan dalam analisis *fracture mechanics*.

Pada tugas akhir ini, dimana penelitian dititikberatkan pada pengaruh *over protection* pada perlindungan katodik dengan metode *impressed current catodic protection* terhadap *plane-strain fracture toughness* baja SS-41, permasalahan dibatasi pada kondisi *linear elastic fracture mechanics*.

3.2 *Linear Elastic Fracture Mechanics* (LEFM)

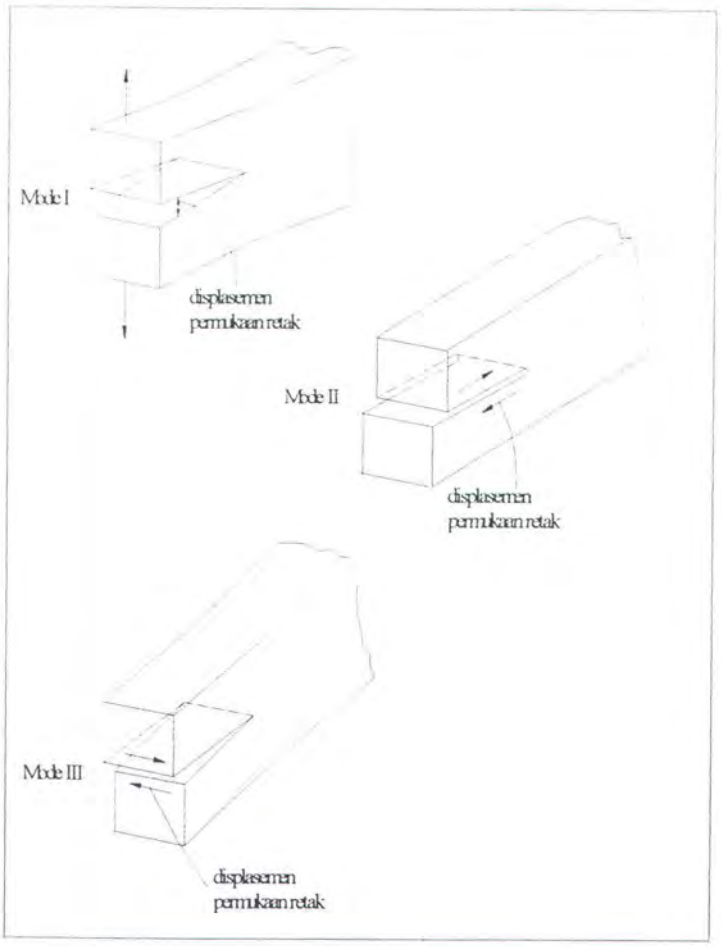
3.2.1 Pedahuluan

Seperti yang telah dijelaskan diawal bahwa *fracture mechanics* adalah suatu metode matematis yang digunakan untuk menganalisis perilaku material yang dalam perkembangannya untuk kondisi *quasistatic* dapat dibagi dua yaitu *Linear Elastic Fracture Mechanics* (LEFM) dan *Elastic Plastic Fracture Mechanics* (EPFM).

Elastic Plastic Fracture Mechanics (EPFM) adalah suatu konsep yang didasarkan pada keseimbangan energi yang disediakan sistem tersebut untuk terjadinya retak. Konsep ini digunakan jika daerah plastis yang timbul pada ujung retak lebih besar bila dibandingkan dengan ukuran retak. Sedangkan *Linear Elastic Fracture Mechanics* (LEFM) didasarkan pada prosedur analisis yang menghubungkan besarnya medan tegangan serta distribusinya disekitar ujung retak dengan tegangan nominal yang bekerja terhadap struktur, bentuk, ukuran dan orientasi dari retak atau diskontinuitas tersebut.

3.2.2 Tegangan Diujung Retak (*Stress Intensity Factor*)

Untuk menganalisis tegangan pada sebuah retak, maka perlu dilakukan pendefinisian jenis retak menurut gerakan relatif dari kedua permukaan. Distribusi tegangan di daerah ujung retak terdiri dari tiga mode seperti terlihat pada gambar 3.4.



Gambar 3.4 Macam bentuk pembebanan

Mode I : *Opening Mode*

Crack opening mode, retak dibuka lebar pada permukaan retakan akibat adanya tegangan tarik yang tegak lurus terhadap bidang penjalaran retak.

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}}\left[\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}}\left[\cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\left[\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right]$$

$$\sigma_y = \upsilon(\sigma_x + \sigma_y),\ \tau_{xz} = \tau_{yz} = 0$$

$$U = \frac{K_I}{G}\left[\frac{r}{(2\pi)}\right]^{\frac{1}{2}}\cos\frac{\theta}{2}\left[1-2\upsilon+\sin^2\frac{\theta}{2}\right]$$

$$V = \frac{K_I}{G}\left[\frac{r}{(2\pi)}\right]^{\frac{1}{2}}\sin\frac{\theta}{2}\left[2-2\upsilon+\cos^2\frac{\theta}{2}\right]$$

$$W = 0 \qquad [3.1]$$

Mode II : *Sliding Mode*

In-plane shear mode, bagian retak searah dengan bidang penjalaran retak yang diakibatkan oleh tegangan geser.

$$\sigma_x = -\frac{K_{II}}{\sqrt{2\pi r}}\left[\sin\frac{\theta}{2}\left(2+\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)\right]$$

$$\sigma_y = \frac{K_{II}}{\sqrt{2\pi r}}\left[\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right]$$

$$\tau_{xy} = \frac{K_{II}}{\sqrt{2\pi r}}\left[\cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right]$$

$$\sigma_y = \upsilon(\sigma_x + \sigma_y),\ \tau_{xz} = \tau_{yz} = 0$$

$$U = \frac{K_{II}}{G}\left[\frac{r}{(2\pi)}\right]^{\frac{1}{2}}\sin\frac{\theta}{2}\left[2-2\upsilon+\cos^2\frac{\theta}{2}\right]$$

$$V = \frac{K_{II}}{G}\left[\frac{r}{(2\pi)}\right]^{\frac{1}{2}}\cos\frac{\theta}{2}\left[-1+2\upsilon+\sin^2\frac{\theta}{2}\right]$$

$$W = 0 \qquad [3.2]$$

Mode III : *Tearing mode*

Out-of-plane shear mode, perambatan retak seperti robekan karena permukaan retak bergeser terhadap penjalaran lainnya dalam arah sejajar tepi takikan. Retak yang diakibatkan tegangan geser yang bekerja pada arah melintang dan membentuk sudut dengan arah penjalaran retak.

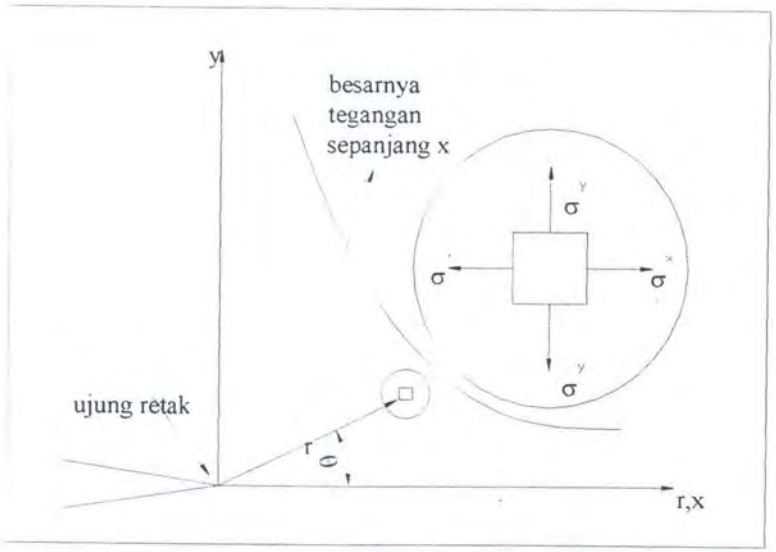
$$\tau_{xz} = -\frac{K_{III}}{\sqrt{2\pi r}} \sin\frac{\theta}{2}$$

$$\tau_{xz} = \frac{K_{III}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}$$

$$\sigma_x = \sigma_y = \sigma_z = \tau_{xy} = 0$$

$$U = \frac{K_{III}}{G}\left[\frac{2r}{(\pi)}\right]^{\frac{1}{2}} \sin\frac{\theta}{2}$$

$$U = V = 0 \qquad [3.3]$$



Gambar 3.5 Distribusi tegangan elastis disekitar ujung retak

Komponen-komponen tegangan dan sistem koordinat r dan θ dapat dilihat pada gambar 3.5 diatas, u, v dan w displasemen kearah x, y, dan z, υ adalah *poison ratio*, G adalah modulus geser elastisitas. Sedangkan K_I, K_{II}, K_{III} adalah faktor intensitas tegangan (SIF) untuk masing masing gerakan relatif perambatan retak yang tergantung pada tipe tegangan dan ukuran dari retak yang terjadi.

Mode I dan mode II merupakan kasus *plane strain* dimana displasemen kearah z adalah sama dengan nol (w = 0), serta mengabaikan penggunaan pangkat yang lebih tinggi, sehingga akan dihasilkan perhitungan pendekatan untuk radius (r) yang mendekati nol pada ujung retak.

3.2.3 Daerah Plastis Ujung Retak (Zona Plastis Irwin)

Setiap struktur pasti akan mengalami tegangan yang kesemuanya akan tergantung pada bentuk retak, ukuran retak, serta konfigurasi dari struktur dengan macam pembebanan atau mode seperti terlihat pada gambar 3.5, yang kesemuanya akan sangat berpengaruh pada *stress intensity factor (SIF)*. Dengan adanya tegangan tersebut maka akan terdapat daerah yang mengelilingi retak pada metal, dimana deformasi plastis muncul. Untuk ukuran zona plastis sementara pertimbangan dibatasi pada *plane-stress*.

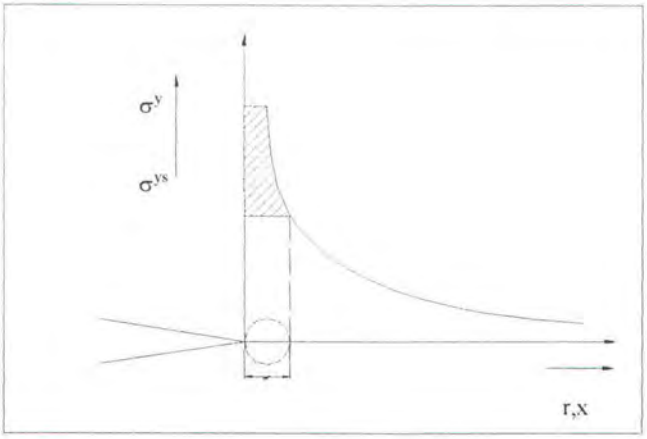
Apabila kita memperhatikan gambar 3.6, besarnya tegangan diujung retak ini dapat ditentukan dengan pendekatan secara matematis dari persamaan yang dikembangkan oleh Irwin. Dari gambar 3.6 dapat diketahui harga σ_y pada θ = 0. Sampai jarak rp^* dari ujung retak, dan dapat dilihat bahwa *stress* lebih

besar dari *yield stress*, σ_{ys}. Untuk perkiraan pertama rp^* adalah ukuran daerah plastis.

$$\sigma_y = \frac{K_I}{\sqrt{2\pi rp^*}} = \sigma_{ys} \qquad \text{atau}$$

$$rp^* = \frac{K_I^{\,2}}{2\pi\sigma_{ys}^{\,2}} = \frac{\sigma^2 a}{2\sigma_{ys}^{\,2}} \qquad [3.4]$$

Irwin berasumsi bahwa munculnya plastisitas membuat retak lebih panjang dari ukuran retak fisik. Akibat plastisitas pada ujung retak ini, displasemen akan lebih besar dan kekakuan lebih kecil dari kasus elastis. Sehingga ukuran retak sebenarnya atau retak efektif sama dengan ukuran retak phisik ditambah koreksi $\delta a + \delta$.



Gambar 3.6 Perkiraan pertama ukuran zona plastik

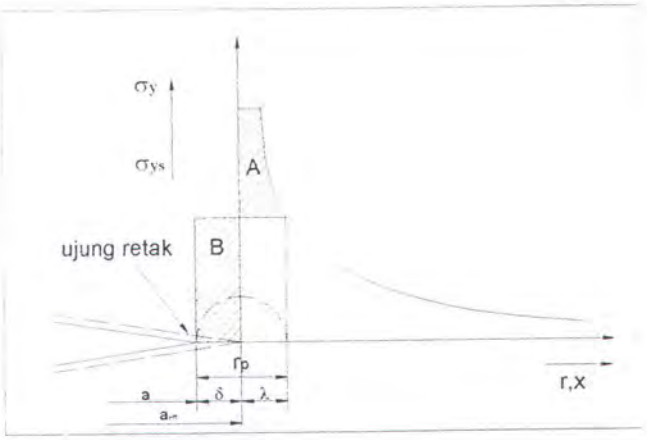
Dengan mengganti ukuran retak fisik a dengan ukuran retak yang lebih besar yaitu $a + \delta$ (gambar 3.7) sehingga distribusi tegangan elastis (σ_y) pada ujung retak efektif dapat diketahui. Tegangan dari ujung retak efektif dibatasi oleh σ_{ys}. Dengan cara yang sama tegangan yang bekerja pada δ di depan retak phisik

besarnya sama dengan tegangan *yield*. Sehingga δ harus cukup besar untuk mengganti beban yang hilang oleh potongan pada daerah A (gambar 3.8) oleh distribusi tegangan elastis. Dalam hal ini luas pada daerah A sama dengan daerah B sehingga besarnya λ pada gambar 3.8 dapat dicari dengan cara sebagai berikut :

$$\sigma_{ys} = \frac{K}{\sqrt{2\pi\lambda}} = \sigma\sqrt{\frac{a+\delta}{2\lambda}} \quad \text{atau} \quad \lambda = \frac{\sigma^2(a+\delta)}{2\sigma_{ys}^{\ 2}} \approx r_p^{\ *} \qquad [3.5]$$

Jika δ amat kecil apabila dibandingkan dengan ukuran retak a, maka dapat diabaikan dan $\lambda = r_p^*$ seperti persamaan 2.6. Dengan luas B sama dengan $\sigma_{ys}\,\delta$, dan dengan ketentuan B = A maka akan didapatkan

$$\delta = r_p^* \quad \text{dan} \quad r_p = \lambda + \delta = 2r_p^* \qquad [3.6]$$

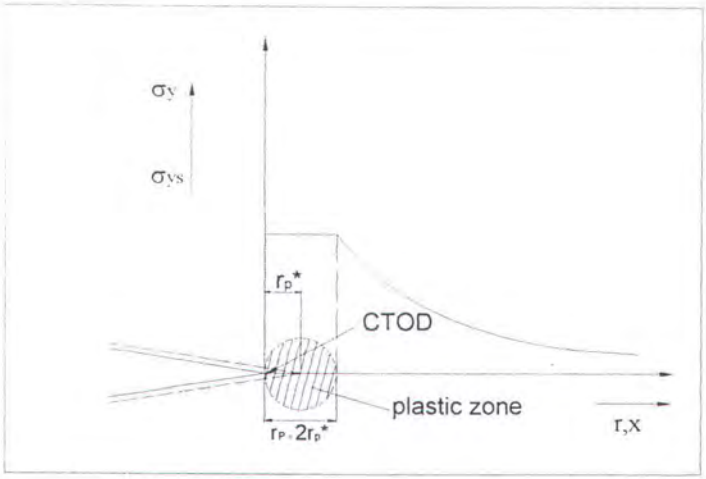


Gambar 3.7 Perkiraan kedua ukuran zona plastik

Seperti kita lihat pada gambar 3.8 besarnya daerah zona plastis adalah dua kali lebih besar dari perkiran zona plastik yang pertama (r_p^*), jadi panjang retak dalah a + r_p^*, sebab δ = r_p^*. Kuantitas r_p^* ditetapkan sebagai koreksi daerah plastik Irwin[6]. Sembarang asumsi menunjukkan bahwa zona plastik memiliki

bentuk *circular*, kondisi ini digambarkan oleh gambar 3.8, dimana retak efektif berakhir pada pusat zona plastik.

Koreksi zona plastik pada persamaan pada persamaan 3.4 bukan untuk kondisi *plane-strain*. Koreksi daerah plastik tersebut digunakan dalam menentukan harga *crack opening displacement* (*COD*).



Gambar 3.8 Koreksi zona plastik Irwin

Harga COD ditentukan dengan persamaan berikut :

$$COD = \frac{4\sigma}{E}\sqrt{\left(a + r_p^*\right)^2 - x^2} \qquad [3.7]$$

Jika harga x = a maka harga *crack tip opening displacement* adalah

$$COD = \frac{4\sigma}{E}\sqrt{\left(a + r_p^*\right)^2 - a^2} \approx \frac{4\sigma}{E}\sqrt{2ar_p^*} = \frac{4}{\pi}\frac{K^2}{E\sigma_{ys}} \qquad [3.8]$$

BAB IV

METODOLOGI PENELITIAN

BAB IV

METODOLOGI PENELITIAN

4.1 Pendahuluan

Pengujian elektrokimia sel tiga elektroda dilakukan untuk memberikan kondisi *over protection* dalam proses perlindungan korosi menggunakan metode *impressed current cathodic protection (ICCP)* terhadap spesimen uji.

Pengujian *fracture* (kepecahan) dilakukan untuk mendapatkan harga *plain strain fracture toughness* atau ketangguhan material dibawah kondisi *plane strain* (K_{Ic}) dengan menggunakan standard ASTM *(American Society for Testing and Materials)* yaitu ASTM E 399 – 83.

Persiapan material dan pengujian material sepenuhnya dilakukan di laboratorium FTK-ITS, yaitu di laboratoruim teknologi mekanik dan laboratorium konstruksi dan kekuatan. Bentuk spesimen dan ukuran telah disesuaikan mengacu pada standard yang digunakan yaitu ASTM E 399 – 83.

Material yang digunakan dalam pengujian adalah material jenis SS-41 yang merupakan jenis material *mild steel* sesuai Standard *JIS (Japanese Industrial Standard)*. Pengujian dilakukan pada kondisi temperatur ruang (30° C). Material didapat dari PT. PAL Indonesia.

4.2 Sel Tiga Elektoda

Pengujian ini dilakukan untuk memberikan potensial perlindungan katodik pada material dan menimbulkan terjadinya absorbsi atom-atom tunggal hidrogen ke dalam material.

4.2.1 Persiapan alat dan bahan

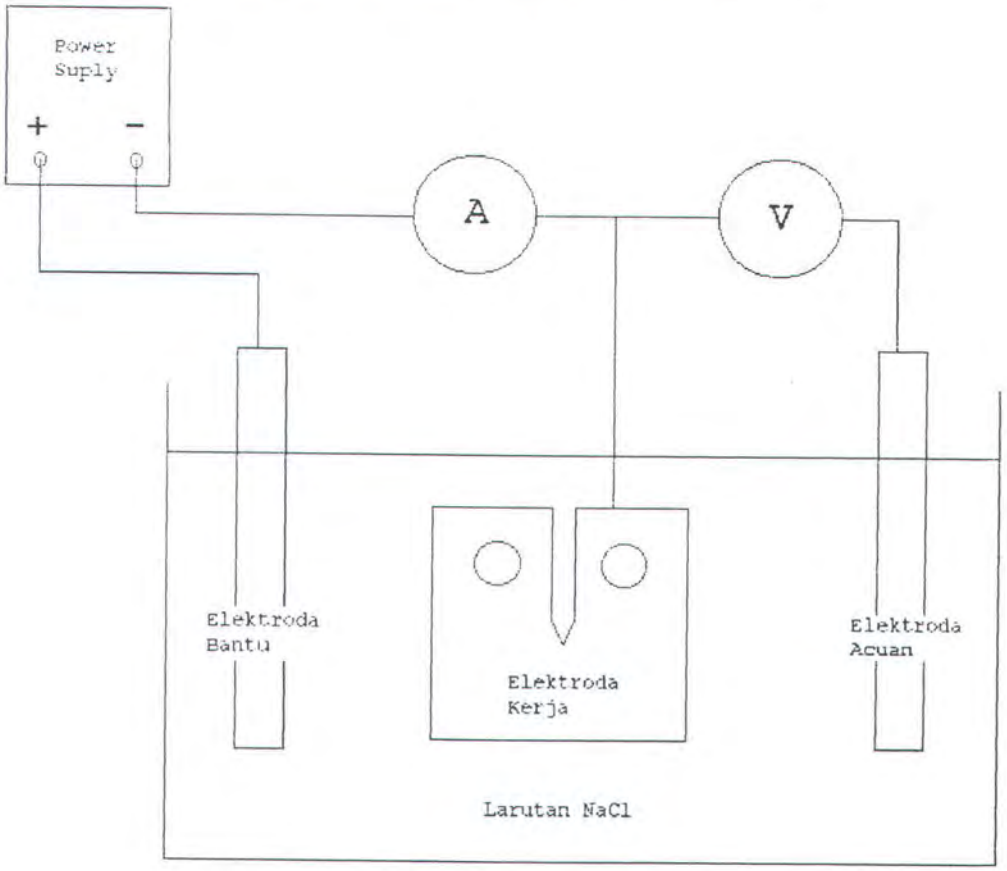
Alat dan bahan yang digunakan dalam pengujian sel tiga elektroda ini adalah sebagai berikut :

- Elektroda kerja : elektroda (material uji) yang sedang diteliti
- Elektroda bantu : elektroda untuk mengangkut arus dalam rangkaian yang terbentuk dalam pengujian dan tidak diperlukan untuk pengukuran potensial. Elektroda yang digunakan adalah batang karbon.
- Elektroda acuan : sebagai titik acuan pengukuran potensial elektroda kerja. Arus yang mengalir melalui elektroda ini harus sekecil-kecilnya sehingga dapat diabaikan, jika tidak elektroda ini akan ikut dalam reaksi sel dan potensialnya tidak lagi konstan. Elektroda yang digunakan adalah kalomel jenuh *(saturated calomel electroda, SCE)*.
- Larutan elektrolit : dipakai adalah air yang mempunyai salinitas 30.
- Sumber GGL : bertindak sebagai penggerak elektroda kerja sedemikian hingga reaksi sel yang dikehendaki berlangsung.

- Galvanometer : pengukur arus yang dapat dibaca hingga miliampere atau bahkan mikroampere.
- Voltmeter : alat untuk mengukur potensial, yang selama pengukuran alat ini tidak boleh teraliri arus.

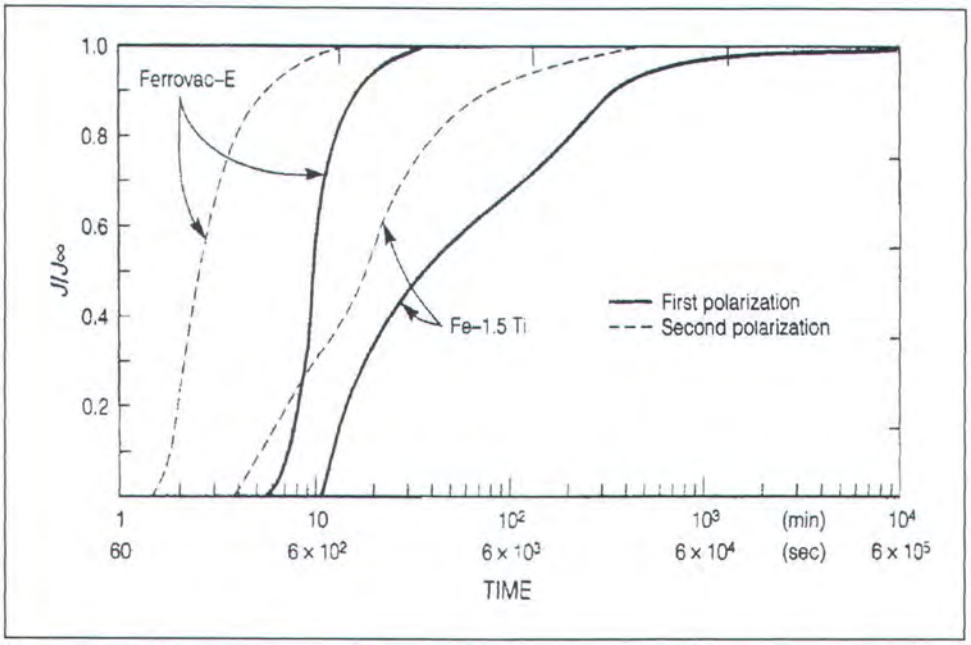
4.2.2 Pelaksanaan pengujian

Alat dan bahan yang sudah tersedia dirangkai seperti gambar 4.1 :



Gambar 4.1 Skema sel tiga elektroda [Trethewey dan Chamberlain, 1988]

Penentuan lama pengujian untuk masing-masing spesimen berdasarkan grafik hubungan antara waktu dan prosentase pengisian hydrogen kedalam ruang kosong pada material seperti yang ditunjukkan pada gambar 4.2 berikut ini :



Gambar 3.2 Hubungan waktu dengan hidrogen yang masuk dan volume ruang kosong *[Jones,1991]*

Keterangan : - J = hidrogen yang masuk
- J∞ = volume ruang kosong di dalam material

Sumbu x menyatakan waktu dan sumbu y menyatakan perbandingan banyaknya hidrogen yang masuk dengan volume ruang kosong yang terdapat didalam material. Dari gambar diatas dapat terlihat bahwa pada waktu 10^4 menit harga J/J∞ mendekati 1,0 yang berarti bahwa hidrogen hampir memenuhi semua ruang kosong di dalam material. Berdasarkan hal tersebut maka dipilih waktu 10^4 menit (7 hari (168 jam)) dengan harapan akan mendapatkan hasil yang baik.

Spesimen uji yang berjumlah sepuluh buah diberi perlakuan pengujian sel tiga elektroda sebagai berikut :

- 2 buah tidak diberi perlakuan sel tiga elektroda.
- 2 buah dialiri tegangan –850 mV SSC selama 7 hari (168 jam).
- 2 buah dialiri tegangan –950 mV SSC selama 7 hari (168 jam).

- 2 buah dialiri tegangan –1050 mV SSC selama 7 hari (168 jam).
- 2 buah dialiri tegangan –1150 mV SSC selama 7 hari (168 jam).

Karena menggunakan *reference electroda SCE* (*Saturated Calomel Electroda*) maka diperlukan perhitungan konversi untuk besarnya potensial yang harus diberikan terhadap spesimen uji.

$E_{Met/Ref} = E_{Met/SHE} - E_{Ref/SHE}$

Pertama-tama dilakukan konversi potensial dari elektroda ref, dalam hal ini SSC ke SHE (*Standard Hydrogen Electroda*). Diketahui data $E_{Met/Ref}$ dalam hal ini $E_{Met/SSC}$ adalah masing-masing : -850 mV SSC, -950 mV SSC, -1050 mV SSC, -1150 mV SSC. $E_{Ref/SHE}$ dimana $E_{SSC/SHE}$ = + 266 mV, sehingga didapat

-850 mV SSC = -584 mV SHE

-950 mV SSC = -684 mV SHE

-1050 mV SSC = -784 mV SHE

-1150 mV SSC = -884 mV SHE

Kemudian potensial tersebut dikonversikan ke SCE. Diketahui data $E_{Ref/SHE}$ dimana $E_{SCE/SHE}$ = + 242 mV, sehingga didapat

-850 mV SSC = -584 mV SHE = -826 mV SCE

-950 mV SSC = -684 mV SHE = -926 mV SCE

-1050 mV SSC = -784 mV SHE = -1026 mV SCE

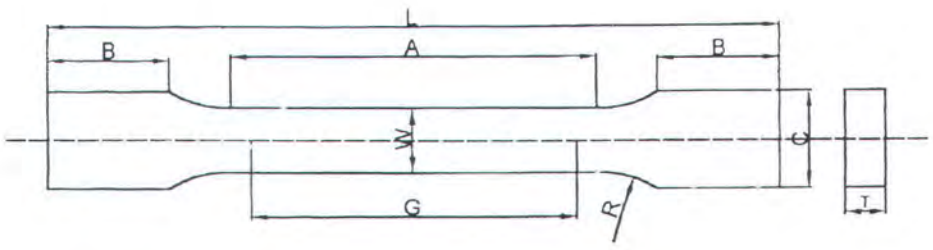
-1150 mV SSC = -884 mV SHE = -1126 mV SCE

4.3 Spesimen Uji Tarik

Uji tarik dilakukan untuk mengetahui *mechanical properties* (sifat-sifat mekanis) dari material baja SS-41 yang meliputi *yield stress* dan *ultimate stress*. Hasil dari uji tarik tersebut digunakan untuk *fracture test* sebagai acuan dalam menentukan skala pembebanan.

Dimensi spesimen sesuai standard ASTM E 8M-85 . Dalam pembuatan spesimen uji tarik, dimensi disesuaikan dengan standard dan menyesuaikan dengan peralatan yang tersedia di laboratorium. Proses pembuatan spesimen dilakukan di laboratorium konstruksi dan kekuatan dan laboratorium teknologi mekanik dengan cara sebagai berikut : material dipotong dengan gergaji sesuai dengan dimensi yang sesuai dengan standard dan dilebihkan sekitar 2 mm. Setelah mendapatkan bentuk yang dikehendaki dilakukan penyekrapan sampai ukuran yang diinginkan yang diikuti dengan pengikiran dan diakhiri dengan penghalusan dengan kertas gosok untuk menghindari terjadinya cacat pada permukaan spesimen.

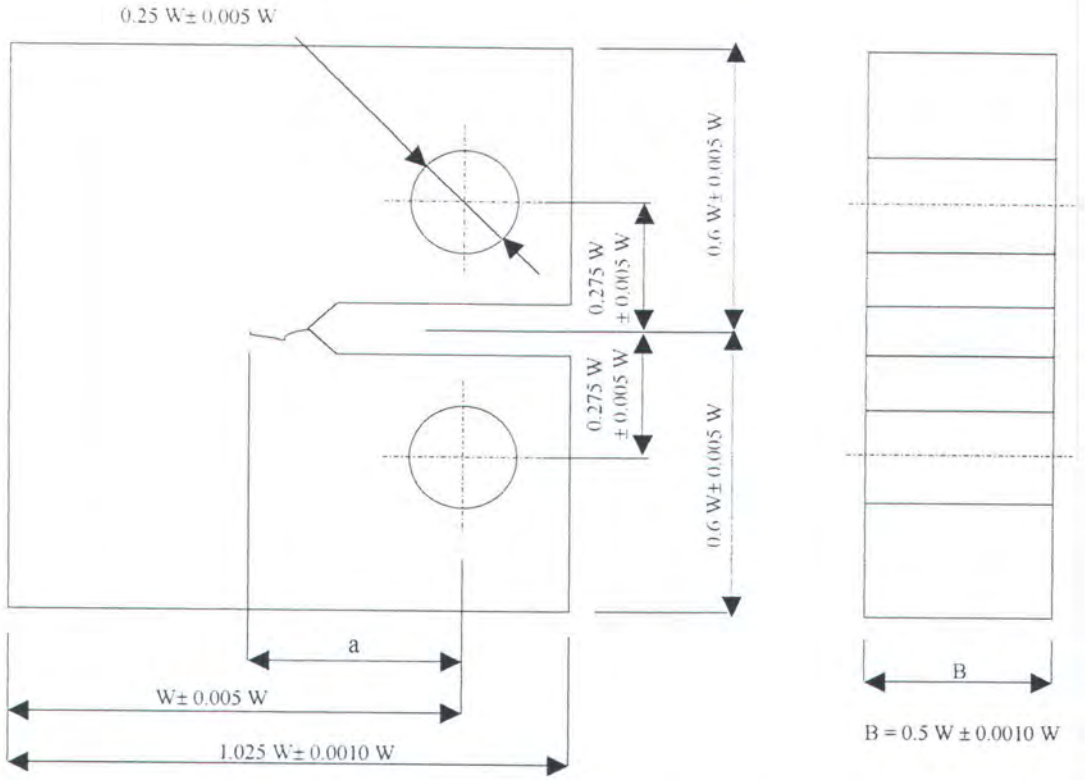
Bentuk dan ukuran spesimen uji tarik yang akan digunakan dalam pengujian seperti pada gambar 4.3.



Gambar 4.3 Dimensi spesimen uji tarik

4.4 Compact Tension Specimen

Material yang dipakai untuk uji *fracture* adalah sama dengan material yang digunakan untuk uji tarik. Bentuk material yang digunakan adalah *compact tension specimen* (CTS). Bentuk dan ukuran spesimen seperti terlihat pada gambar 4.4.



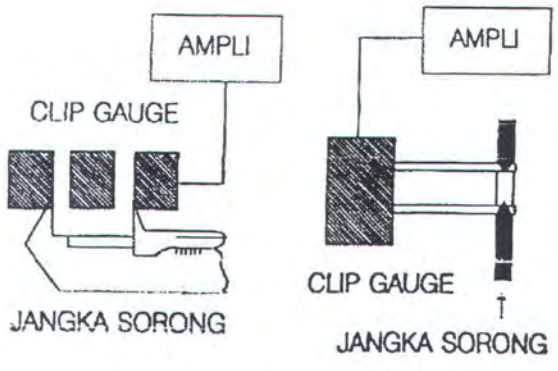
Gambar 4.4 Bentuk dan dimensi *compact tension specimen*

Proses pembuatan masing-masing material sama, yaitu dengan memotong material menggunakan gergaji mesin sesuai dengan panjang dan lebar yang dibutuhkan dan dilebihkan (± 2 mm) dari standard yang digunakan. Kemudian dilakukan pengukuran ulang untuk mendapatkan bentuk yang dikehendaki. Setelah sesuai dengan dimensi yang diinginkan maka dilakukan penyekrapan sampai ukuran yang sebenarnya.

Untuk pembuatan retak dilakukan dengan menggunakan gergaji mesin sesuai dengan panjang retak yang diinginkan dan untuk pembuatan retak fatigue pembuatannya dengan menggunakan gergaji tangan yang telah digerinda mata gergajinya hingga lancip untuk mendapatkan bentuk retak fatigue yang diinginkan. Bentuk dan ukuran retak yang digunakan adalah *straight through notch.*

4.5 Kalibrasi

Sebelum *clip gauge* dipasang pada spesimen *compact tension specimens* pada saat melakukan percobaan yang sesungguhnya, maka diperlukan suatu kalibrasi untuk mengecek kebenaran dari penentuan *displacement* relatif dari *knife edge* dengan pembacaan secara langsung *strain indicator* pada *amplifier.* Kalibrasi dilakukan dengan menempatkan *clip gauge* pada jangka sorong, seperti terlihat pada gambar 4.5.



Gambar 4.5 Pelaksanaan kalibrasi dengan jangka sorong

Pelaksanaan kalibrasi ini dilakukan sebanyak 2 kali yaitu kalibrasi I dan kalibrasi II, masing-masing kalibrasi dilakukan sebanyak 3 kali eksperimen,

sehingga didapatkan rata-rata dari ketiga eksperimen tersebut. Dari data-data kalibrasi tersebut diperoleh persamaan regresi. Untuk mendapatkan hasil yang lebih baik, dalam pelaksanaan kalibrasi tersebut *step* atau pertambahan *displacement* pada jangka sorong harus kecil. Semakin kecil *step* yang diberikan semakin baik data yang diperoleh.

4.6 Pengujian Tarik

Pengujian tarik merupakan pengujian statis yang dilakukan mendapatkan *mechanical properties* (sifat mekanis statis) material, yaitu tegangan *ultimate* dan tegangan *yield*. Jumlah spesimen uji satu buah dan pengujian dilakukan pada temperatur ruang 30° C. Pengujian dilakukan dengan mesin uji statis *(Universal Testing Machine)*. Dari pengujian statis tersebut akan didapatkan *stress-strain diagram* (diagram tegangan-regangan)

Dari grafik dapat diketahui tegangan *ultimate* (σ_{ult}) dan tegangan *yield* (σ_{ys}). Tegangan *ultimate* merupakan tegangan yang tertinggi yang dapat diterima material, sedangkan tegangan *yield* adalah merupakan batas daerah elastis dengan daerah plastis. Secara grafis tegangan *yield* dapat ditentukan dari diagram tegangan-regangan dimana pada titik tersebut beban tertahan atau turun sedikit, kemudian naik lagi hingga mencapai beban maksimum. Pada beberapa material titik *yield* tidak terlihat. Untuk mengetahui besarnya tegangan *yield* (σ_{ys}) pada material tersebut, yaitu dengan menggunakan metode *offset* yang mengacu pada ASTM E 8M-85 , dimana untuk bahan yang tidak mempunyai titik luluh

yang tidak dapat ditentukan secara baik, maka dengan menggunakan metode *offset* ini dapat ditentukan besarnya *yield strenght* (offset = 2 %).

4.7 Pengujian Kepecahan

Pengujian kepecahan *(fracture test)* dilakukan dengan menggunakan metode *Crack Opening Displacement* (COD) yang selanjutnya nanti dapat digunakan untuk menentukan harga *fracture toughness* (K_{Ic}). Pengujian dilakukan pada temperatur ruang (30^{o} C). Pengujian dilakukan dengan mesin uji statis *(Universal Testing Machine)*. Bentuk spesimen adalah *compact tension specimen* atau *CT spesiment* sesuai dengan standard ASTM E 399 – 83.

Langkah perhitungan dalam menentukan harga K_{IC} :

1. Dari hasil pengujian didapat grafik *Load-Displacement*.
2. Dari grafik *Load-Displacement* dibuat garis *scan offset* 5 % sehingga didapat harga P_Q.
3. Perhitungan K_Q dengan rumus sebagai berikut :

$$K_Q = \frac{P_Q}{BW^{1/2}} f\left(\frac{a}{W}\right)$$

$$f\left(\frac{a}{W}\right) = \left[29.6\left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2}\right]$$

Untuk besarnya $f\left(\frac{a}{W}\right)$ untuk masing-masing nilai $\left(\frac{a}{W}\right)$ adalah sebagai berikut:

Tabel 4.1. Hubungan antara $f\left(\frac{a}{W}\right)$ dengan $\left(\frac{a}{W}\right)$.

a/W	f (a/W)
0.500	9.60
0.505	9.68
0.510	9.90
0.515	10.05
0.520	10.21
0.525	10.37
0.530	10.54
0.535	10.71
0.540	10.89
0.545	11.07
0.550	11.26

Dimana:

P_Q = Beban yang ditentukan (kN)

B = Tebal spisemen (cm)

W = Lebar efektif (cm)

A = Panjang retak (cm)

4. Menentukan kriteria ukuran dimensi dari spisemen untuk menentukan harga K_Q yang ditetapkan sebagai nilai K_{IC}.

$$a \geq 2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2$$

$$B \geq 2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2$$

$$W \geq 5.0\left(\frac{K_Q}{\sigma_{ys}}\right)^2$$

5. Apabila harga perhitungan sesuai dengan di atas maka harga $K_Q = K_{IC}$ sedangkan jika tidak maka dipakai *strength ratio* R untuk menghitung ketangguhan material.

BAB V

ANALISIS DAN PEMBAHASAN HASIL PENGUJIAN

BAB V

ANALISIS DAN PEMBAHASAN HASIL PENGUJIAN

5.1 Pengumpulan Data Hasil Pengujian.

Data-data dari kalibrasi *clip gauge* yang dilakukan untuk mengecek kebenaran dari *displacement* relatif *knife edge* dengan pembacaan secara langsung *strain indikator* pada *amplifier* adalah sebagai berikut:

Kalibrasi I

Skala pada jangka sorong yang digunakan :

- Minimum : 7.00 mm
- Maksimum : 9.00 mm
- *Step* atau langkah : 0.20 mm

Tabel 5.1 Hasil kalibrasi I.

No	Displasmen	Langkah	CG 1	CG 2	CG 3	CG rata-rata
1	7.0	0.0	1815	1608	1115	1513
2	7.2	0.2	2053	1970	1596	1873
3	7.4	0.4	2640	2510	2161	2437
4	7.6	0.6	3102	2960	2700	2921
5	7.8	0.8	3554	3440	3180	3391
6	8.0	1.0	3983	3800	3630	3804
7	8.2	1.2	4350	4230	4101	4227
8	8.4	1.4	4686	4604	4600	4630
9	8.6	1.6	5280	4983	5150	5138
10	8.8	1.8	5718	5294	5570	5527
11	9.0	2.0	6182	5693	5920	5932

Dari tabel 5.1 kalibrasi I maka didapatkan persamaan regresi sebagai berikut : $Y = 2223.7576\ X + 29.2$

Kalibrasi II

Skala pada jangka sorong yang digunakan :

- Minimum : 6.00 mm
- Maksimum : 9.00 mm
- *Step* atau langkah : 0.2 mm

Tabel 5.2. Hasil kalibrasi II.

No	Displasmen	Langkah	CG 1	CG 2	CG 3	CG rata-rata
1	6.0	0.0	-2056	-1870	-2650	-2192
2	6.2	0.2	-1652	-1400	-2120	-1724
3	6.4	0.4	-1140	-659	-1550	-1116
4	6.6	0.6	-570	-30	-930	-510
5	6.8	0.8	-30	380	-360	-3
6	7.0	1.0	660	1030	130	607
7	7.2	1.2	1230	1640	660	1177
8	7.4	1.4	1850	2200	1200	1750
9	7.6	1.6	2307	2750	1640	2232
10	7.8	1.8	2800	3200	2108	2703
11	8.0	2.0	3320	3770	2620	3237
12	8.2	2.2	3850	4340	3070	3753
13	8.4	2.4	4510	4910	3650	4357
14	8.6	2.6	5000	5240	4260	4833
15	8.8	2.8	5509	5770	4870	5383
16	9.0	3.0	6000	6140	5730	5957

Dari tabel 5.2 kalibrasi II maka didapatkan persamaan regresi sebagai berikut: $Y = 2704.1071\ X - 41.0508$

Uji tarik dilakukan untuk mendapatkan acuan dalam penentuan skala pembebanan yang dipakai untuk *fracture test*. Pengujian ini dilakukan pada temperatur ruang (30° C). Rumus yang digunakan untuk perhitungan *yield stress* dan *ultimate stress* adalah :

$$\sigma_y = \frac{P_y}{A_o} \text{ x } 102 \quad [\text{kgf/mm}^2] \qquad [5.1]$$

$$\sigma_u = \frac{P_u}{A_o} \text{ x } 102 \quad [\text{kgf/mm}^2] \qquad [5.2]$$

Hasil uji tarik adalah sebagai berikut :

Tabel 5.3. Hasil uji tarik.

Tebal (mm)	Lebar (mm)	Luas A_0 (mm^2)	P_{Yield} (kN)	$P_{Ultimate}$ (kN)	σ_{Yield} (kgf/mm^2)	$\sigma_{Ultimate}$ (kgf/mm^2)
12.5	17.5	218.75	107.5	159	50.13	74.14

Dari hasil uji tarik ditentukan memakai skala pembebanan 100 kN pada mesin uji statis *(Universal Testing Machine)* untuk *fracture test* dengan pencatatan *displacement* setiap penambahan beban 2 kN.

Hasil dari *fracture test* diperoleh data-data sebagai berikut yang kemudian digunakan untuk membuat kurva *Load-Displacement.*

Tabel 5.4. Data hasil *fracture toughness* spesimen I A.

Material uji : I A
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : 0 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2821	0	0	0	0
2	-2677	144	0.052	0.038	0.045
4	-2537	284	0.115	0.090	0.102
6	-2396	425	0.178	0.142	0.160
8	-2247	574	0.245	0.197	0.221
10	-2090	731	0.316	0.255	0.285
12	-1896	925	0.403	0.327	0.365
14	-1671	1150	0.504	0.410	0.457
16	-1409	1412	0.622	0.507	0.564
18	-948	1873	0.829	0.677	0.753
20	1144	3965	1.770	1.451	1.610
20.4	3210	6031	2.699	2.215	2.457

Tabel 5.5. Data hasil *fracture toughness* spesimen I B.

Material uji : I B
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : 0 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-1724	0	0	0	0
2	-1547	177	0.066	0.050	0.058
4	-1378	346	0.142	0.113	0.128
6	-1193	531	0.226	0.181	0.203
8	-1027	697	0.300	0.243	0.271
10	-850	874	0.380	0.308	0.344
12	-628	1096	0.480	0.390	0.435
14	-355	1369	0.602	0.491	0.547
16	-28	1696	0.750	0.612	0.681
18	500	2224	0.987	0.807	0.897
20	2350	4074	1.819	1.491	1.655
21	4158	5882	2.632	2.160	2.396

Tabel 5.6. Data hasil *fracture toughness* spesimen II A.

Material uji : II A
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -850 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2052	0	0	0	0
2	-1863	189	0.072	0.055	0.063
4	-1693	359	0.148	0.118	0.133
6	-1537	515	0.218	0.175	0.197
8	-1338	714	0.308	0.249	0.278
10	-1152	900	0.392	0.318	0.355
12	-886	1166	0.511	0.416	0.464
14	-541	1511	0.666	0.544	0.605
16	-32	2020	0.895	0.732	0.814
17	984	3036	1.352	1.108	1.230
17.8	3756	5808	2.599	2.133	2.366

Tabel 5.7. Data hasil *fracture toughness* spesimen II B.

Material uji : II B
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -850 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2229	0	0	0	0
2	-2048	181	0.068	0.052	0.060
4	-1896	333	0.137	0.108	0.122
6	-1768	461	0.194	0.155	0.175
8	-1595	634	0.272	0.219	0.246
10	-1407	822	0.357	0.289	0.323
12	-1200	1029	0.450	0.365	0.407
14	-960	1269	0.558	0.454	0.506
16	-618	1611	0.711	0.581	0.646
18	298	2527	1.123	0.919	1.021
19	3649	5878	2.630	2.159	2.394

Tabel 5.8. Data hasil *fracture toughness* spesimen III A.

Material uji : III A
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -950 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2120	0	0	0	0
2	-1946	174	0.065	0.049	0.057
4	-1781	339	0.139	0.110	0.125
6	-1652	468	0.197	0.158	0.178
8	-1509	611	0.262	0.211	0.236
10	-1322	798	0.346	0.280	0.313
12	-1120	1000	0.437	0.355	0.396
14	-883	1237	0.543	0.442	0.493
16	-559	1561	0.689	0.562	0.625
18	98	2218	0.984	0.805	0.895
19	1865	3985	1.779	1.459	1.619
19.3	3480	5600	2.505	2.056	2.280

Tabel 5.9. Data hasil *fracture toughness* spesimen III B.

Material uji : III B
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -950 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-3967	0	0	0	0
2	-3800	167	0.062	0.047	0.054
4	-3690	277	0.111	0.087	0.099
6	-3532	435	0.182	0.146	0.164
8	-3381	586	0.250	0.202	0.226
10	-3172	795	0.344	0.279	0.312
12	-2953	1014	0.443	0.360	0.401
14	-2685	1282	0.563	0.459	0.511
16	-2282	1685	0.745	0.608	0.676
18	-420	3547	1.582	1.297	1.439
18.6	1600	5567	2.490	2.044	2.267

Tabel 5.10. Data hasil *fracture toughness* spesimen IV A.

Material uji : IV A
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -1050 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-1876.000	0	0	0	0
2	-1730.000	146	0.053	0.039	0.046
4	-1574.000	302	0.123	0.097	0.110
6	-1442.000	434	0.182	0.145	0.164
8	-1293.000	583	0.249	0.200	0.225
10	-1110.000	766	0.331	0.268	0.300
12	-908.000	968	0.422	0.343	0.382
14	-668.000	1208	0.530	0.432	0.481
16	-345.000	1531	0.675	0.551	0.613
18	467.000	2343	1.040	0.851	0.946
18.8	3500.000	5376	2.404	1.973	2.189

Tabel 5.11. Data hasil *fracture toughness* spesimen IV B .

Material uji : IV B
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -1050 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2577	0	0	0	0
2	-2426	151	0.055	0.041	0.048
4	-2279	298	0.121	0.095	0.108
6	-2127	450	0.189	0.151	0.170
8	-1966	611	0.262	0.211	0.236
10	-1787	790	0.342	0.277	0.310
12	-1588	989	0.432	0.351	0.391
14	-1361	1216	0.534	0.435	0.484
16	-1087	1490	0.657	0.536	0.596
18	-508	2069	0.917	0.750	0.834
19	880	3457	1.541	1.263	1.402
19.6	2880	5457	2.441	2.003	2.222

Tabel 5.12. Data hasil *fracture toughness* spesimen V A .

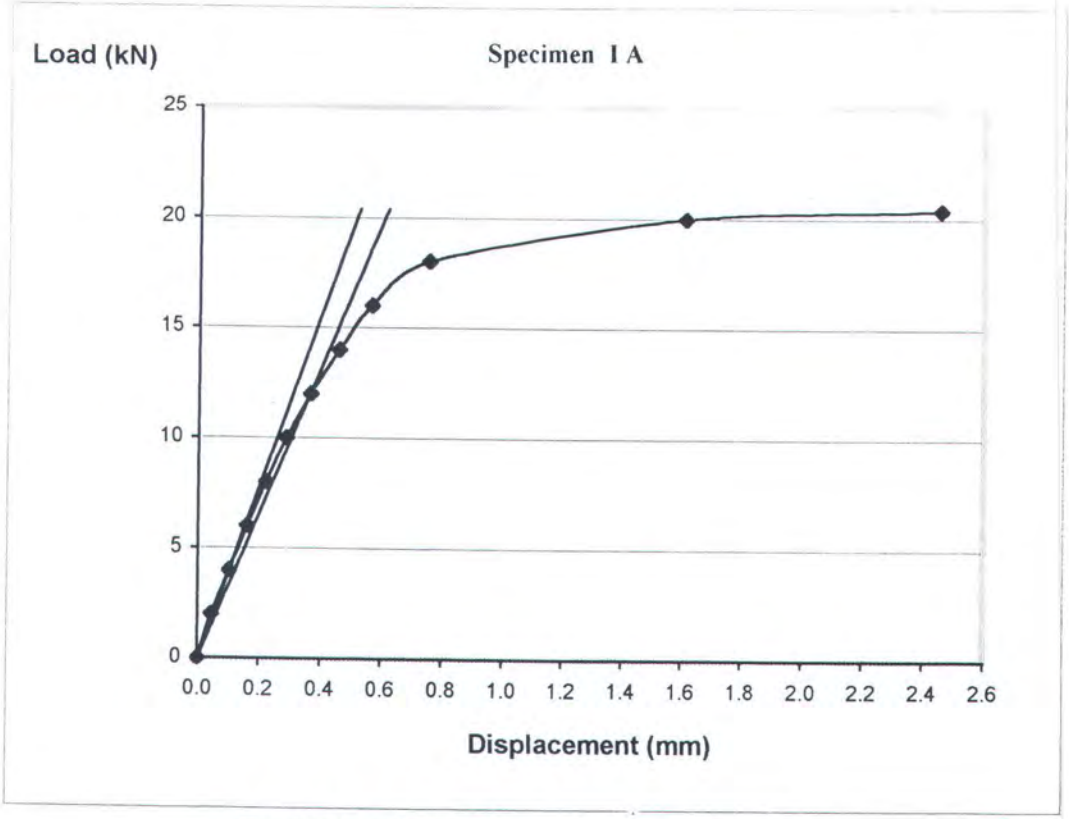
Material uji : V A
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -1150 mV SCC

Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2783	0	0	0	0
2	-2630	153	0.056	0.041	0.049
4	-2483	300	0.122	0.096	0.109
6	-2322	461	0.194	0.155	0.175
8	-2140	643	0.276	0.223	0.249
10	-1935	848	0.368	0.298	0.333
12	-1717	1066	0.466	0.379	0.423
14	-1468	1315	0.578	0.471	0.525
16	-1123	1660	0.733	0.599	0.666
18	-90	2693	1.198	0.981	1.089
18.8	2480	5263	2.354	1.931	2.142

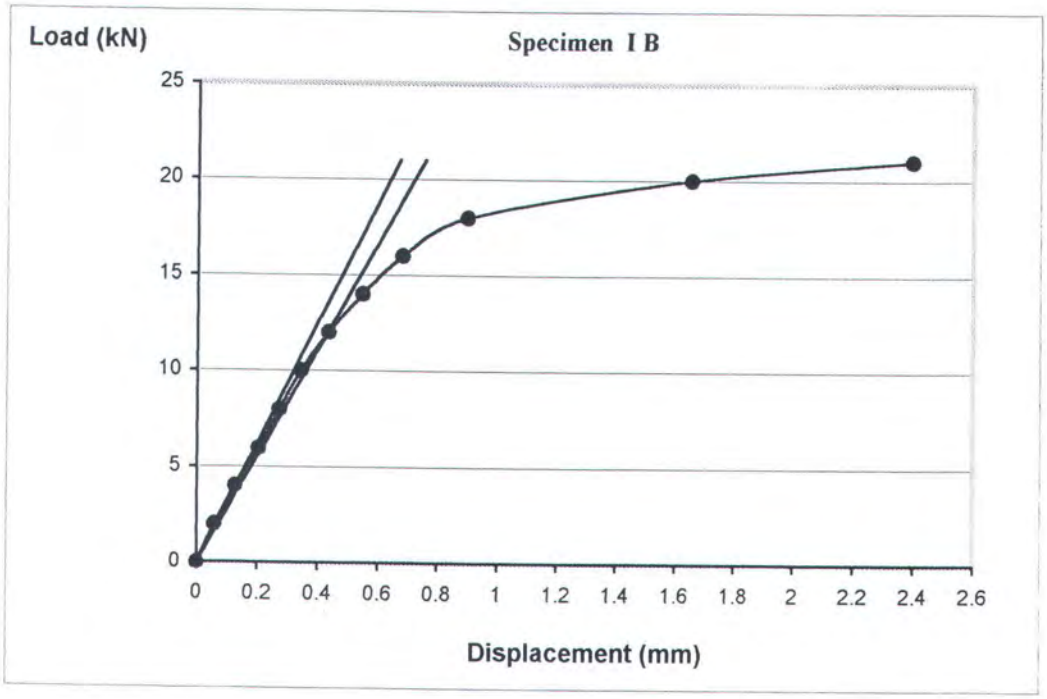
Tabel 5.13. Data hasil *fracture toughness* spesimen V B .

Material uji : V B
B (tebal matrial) : 1.750 cm
a (panjang retak) : 1.925 cm
W (lebar efektif) : 3.500 cm
Potensial : -1150 mV SCC

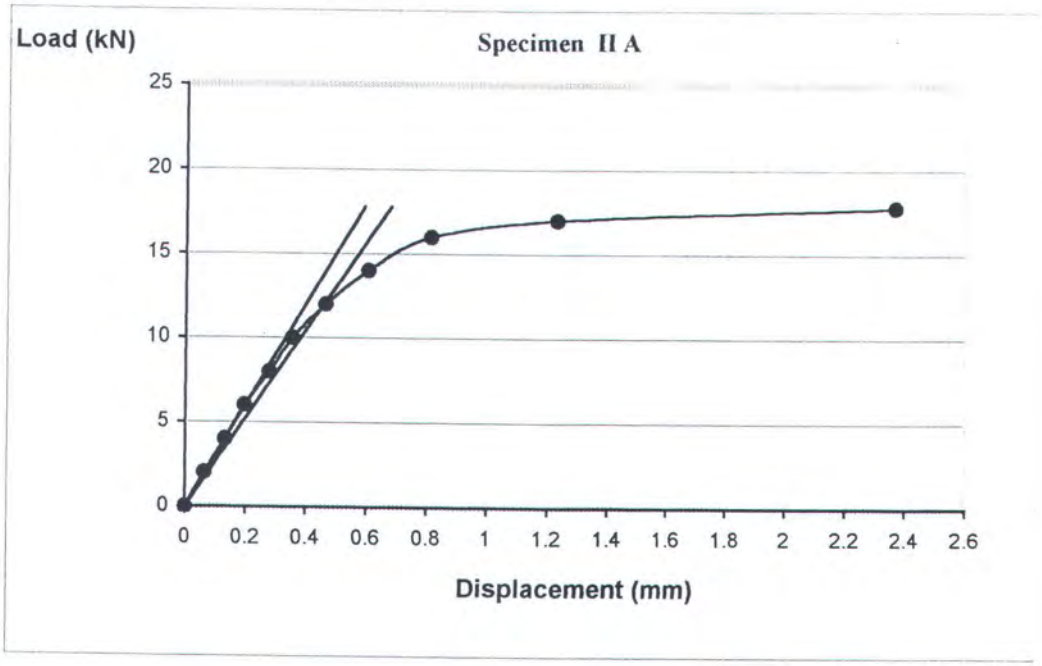
Beban (kN)	Clip Gauge	Langkah	Kalibrasi 1 (mm)	Kalibrasi 2 (mm)	Displacemen rata-rata (mm)
0	-2382	0	0	0	0
2	-2231	151	0.055	0.041	0.048
4	-2079	303	0.123	0.097	0.110
6	-1925	457	0.192	0.154	0.173
8	-1760	622	0.267	0.215	0.241
10	-1574	808	0.350	0.284	0.317
12	-1370	1012	0.442	0.359	0.401
14	-1138	1244	0.546	0.445	0.496
16	-835	1547	0.683	0.557	0.620
18	-126	2256	1.001	0.819	0.910
19	1760	4142	1.849	1.517	1.683
19.2	2800	5182	2.317	1.901	2.109



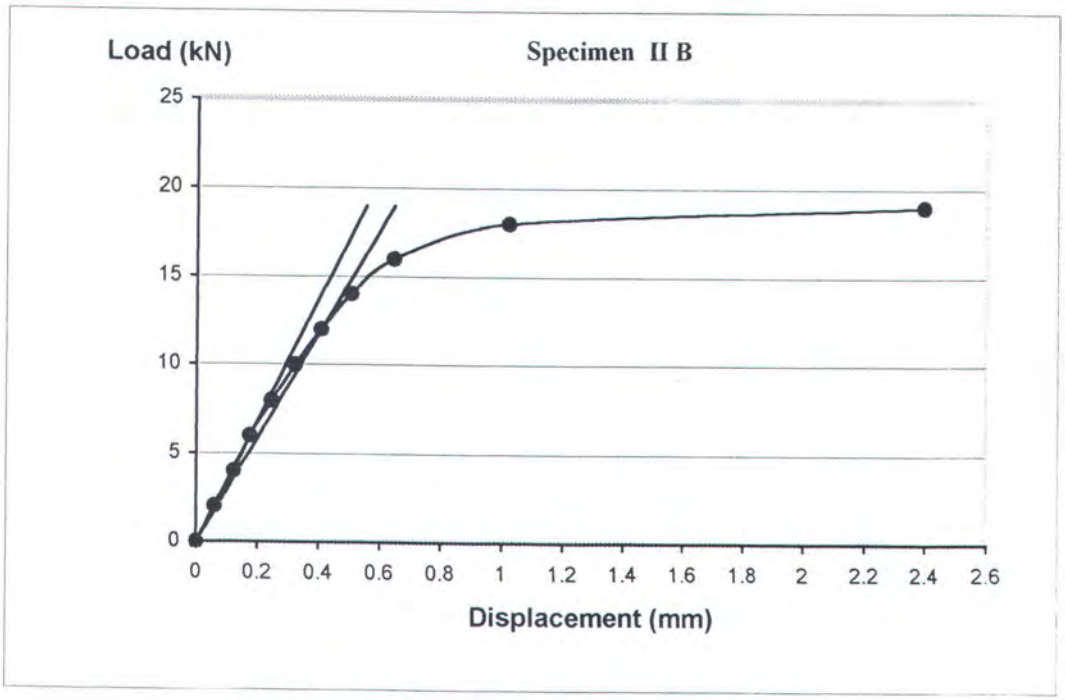
Gambar 5.1. Grafik *load-displacement* spesimen I A



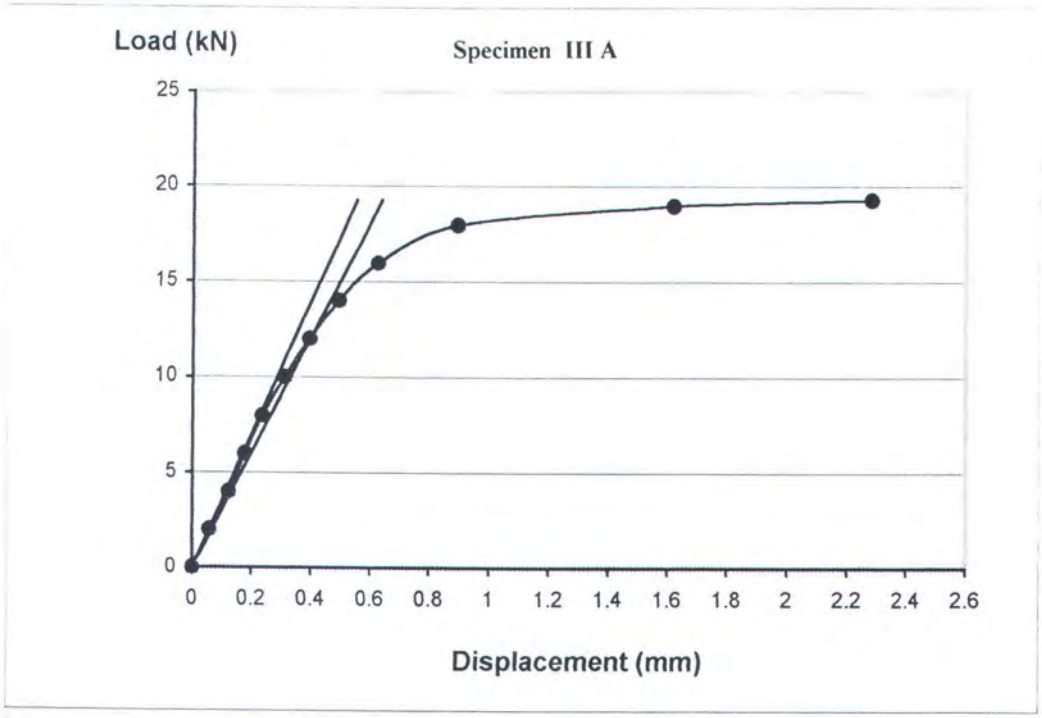
Gambar 5.2. Grafik *load-displacement* spesimen I B



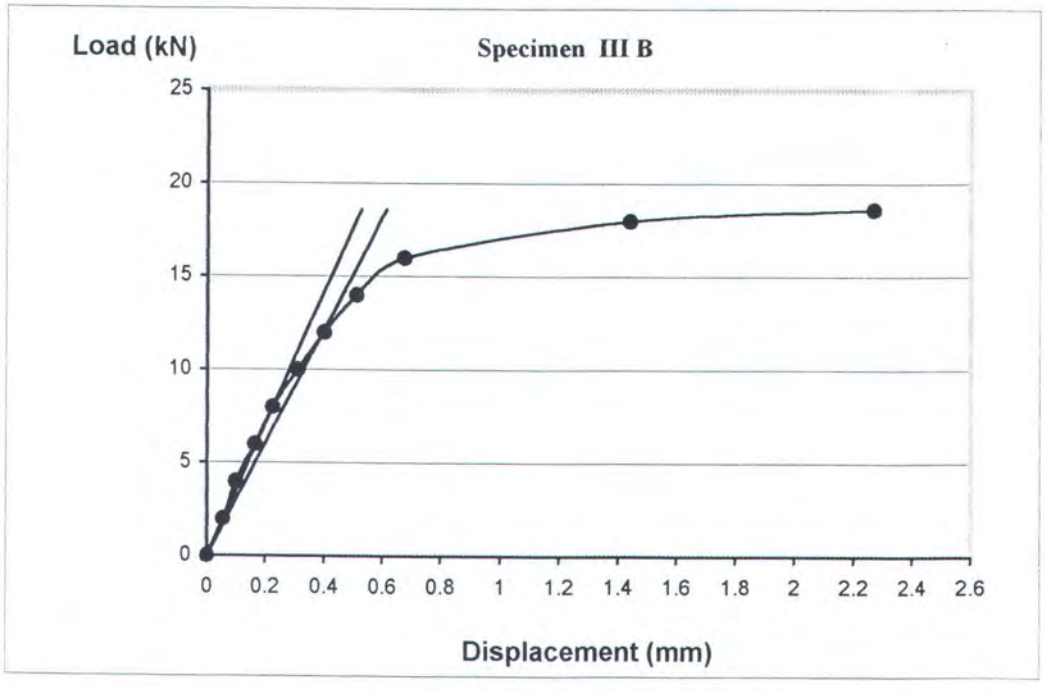
Gambar 5.3. Grafik *load-displacement* spesimen II A



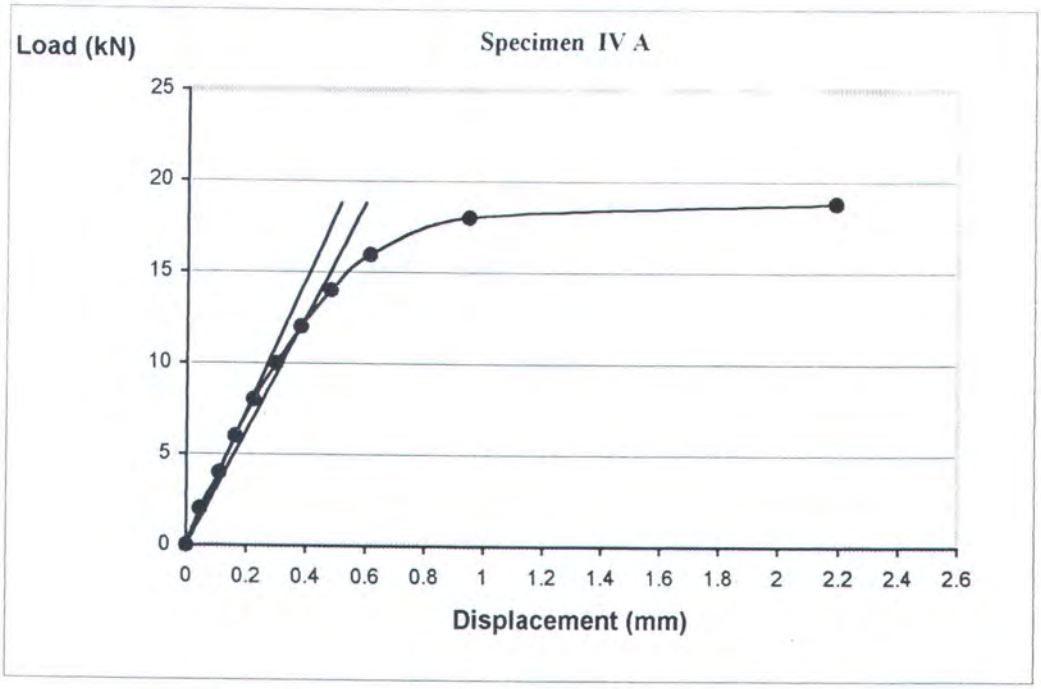
Gambar 5.4. Grafik *load-displacement* spesimen II B



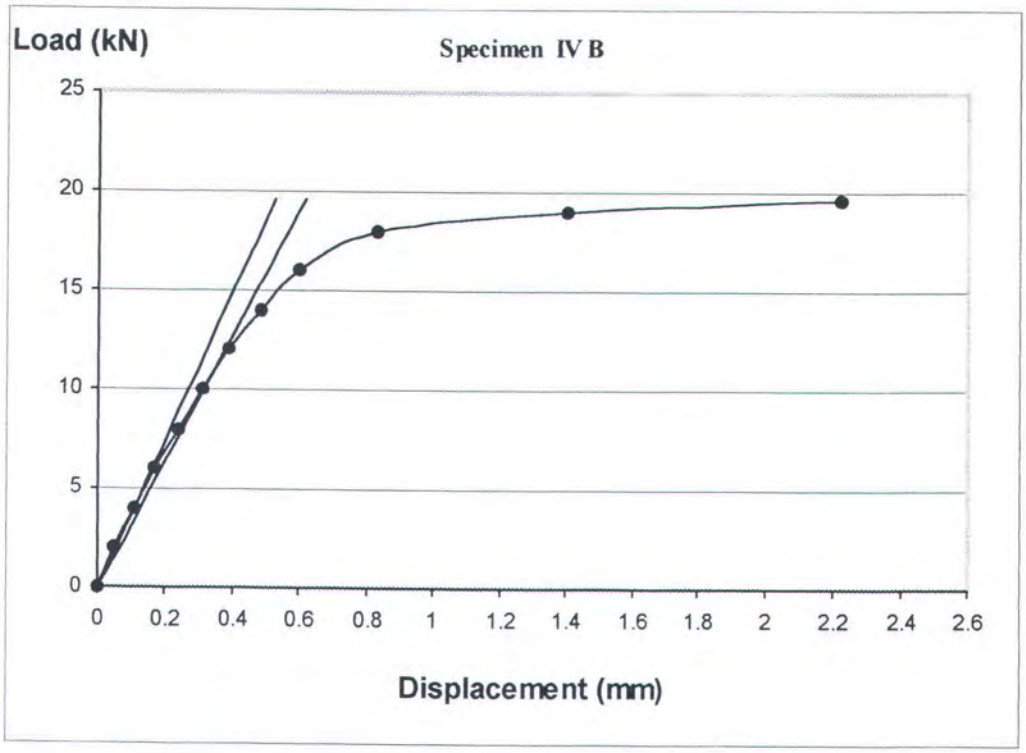
Gambar 5.5. Grafik *load-displacement* spesimen III A



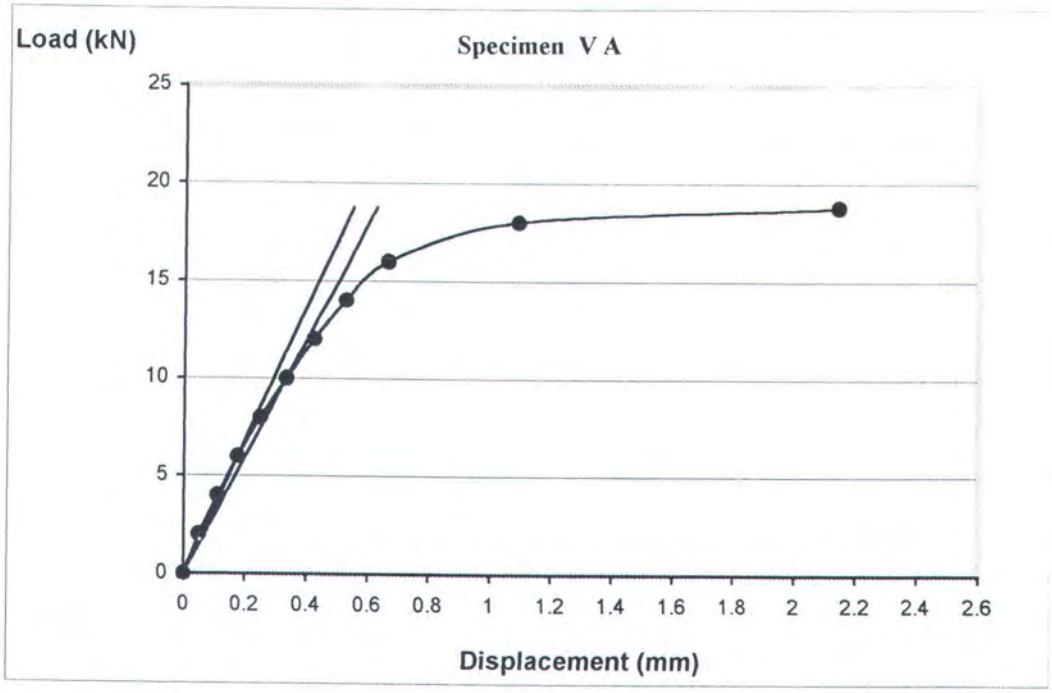
Gambar 5.6. Grafik *load-displacement* spesimen III B



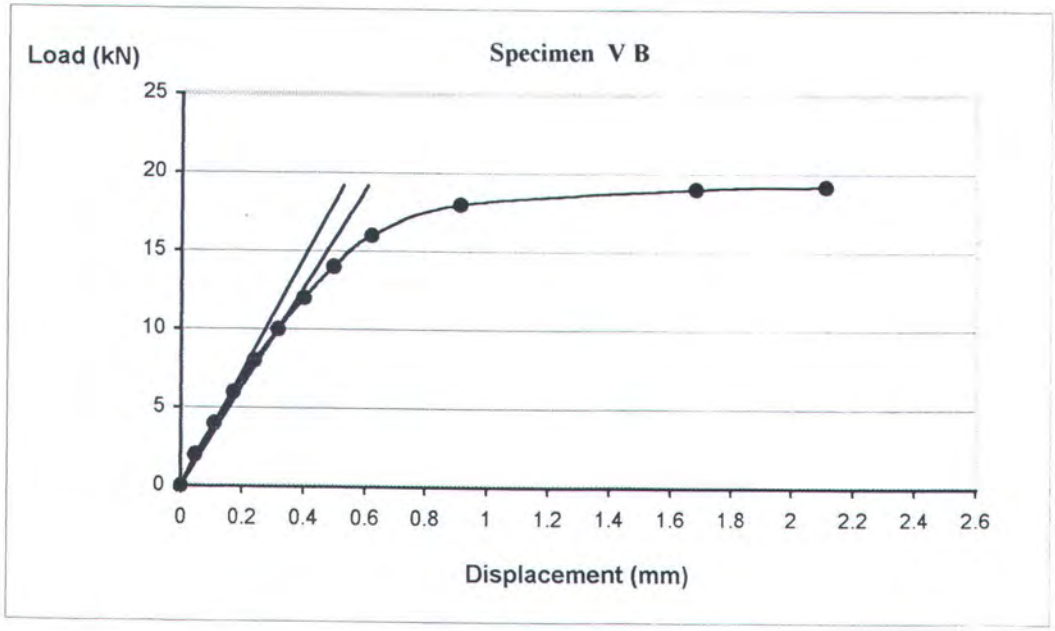
Gambar 5.7. Grafik *load-displacement* spesimen IV A



Gambar 5.8. Grafik *load-displacement* spesimen IV B



Gambar 5.9. Grafik *load-displacement* spesimen V A



Gambar 5.10. Grafik *load-displacement* spesimen V B

Hasil perhitungan K_{IC} untuk masing-masing spesimen adalah sebagai berikut:

Tabel 5.14. Hasil perhitungan K_Q

Material uji	B (cm)	W (cm)	a (cm)	a/W	f (a/W)	K_Q ($kN/cm^{3/2}$)
I A	1.75	3.5	1.925	0.550	11.260	41.271
I B	1.75	3.5	1.925	0.550	11.260	41.271
II A	1.75	3.5	1.925	0.550	11.260	41.271
II B	1.75	3.5	1.925	0.550	11.260	41.271
III A	1.75	3.5	1.925	0.550	11.260	41.271
III B	1.75	3.5	1.925	0.550	11.260	39.552
IV A	1.75	3.5	1.925	0.550	11.260	41.271
IV B	1.75	3.5	1.925	0.550	11.260	37.832
V A	1.75	3.5	1.925	0.550	11.260	34.393
V B	1.75	3.5	1.925	0.550	11.260	34.393

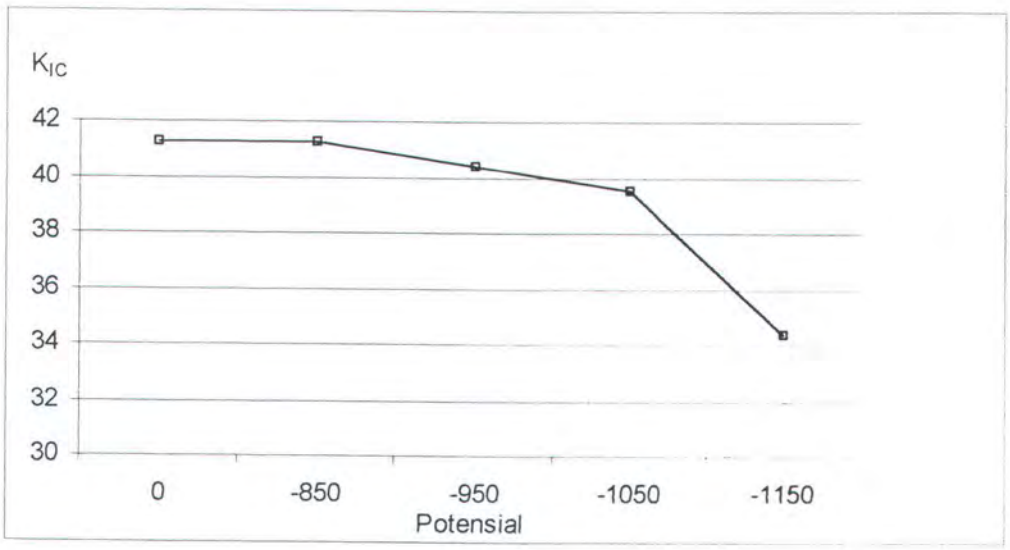
Tabel 5.15. Hasil perhitungan K_{IC}

Material Uji	B (cm)	W (cm)	a (cm)	$2.5 (K_{1C}/\sigma ys)^2$ (cm)	$5.0 (K_{1C}/\sigma ys)^2$ (cm)	K_{1C} ($kN/cm^{3/2}$)
I A	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
I B	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
II A	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
II B	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
III A	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
III B	1.75	3.5	1.925	1.556	3.112	$K_{1C} = K_Q$
IV A	1.75	3.5	1.925	1.694	3.389	$K_{1C} = K_Q$
IV B	1.75	3.5	1.925	1.424	2.848	$K_{1C} = K_Q$
V A	1.75	3.5	1.925	1.177	2.353	$K_{1C} = K_Q$
V B	1.75	3.5	1.925	1.177	2.353	$K_{1C} = K_Q$

Maka hasil perhitungan harga K_{1C} masing-masing material uji adalah sebagai berikut:

Tabel 5.16. Hasil perhitungan harga K_{IC} material uji.

Potensial (mV SSC)	Material	K_{IC} ($kN/cm^{3/2}$)	K_{IC} ata-rata ($kN/cm^{3/2}$)
0	I A	41.271	41.271
	I B	41.271	
-850	II A	41.271	41.271
	II B	41.271	
-950	III A	41.271	40.411
	III B	39.552	
-1050	IV A	41.271	39.552
	IV B	37.832	
-1150	VA	34.393	34.393
	VB	34.393	



Gambar 5.11 Grafik nilai K_{IC} material uji.

5.2 Analisis Hasil Pengujian

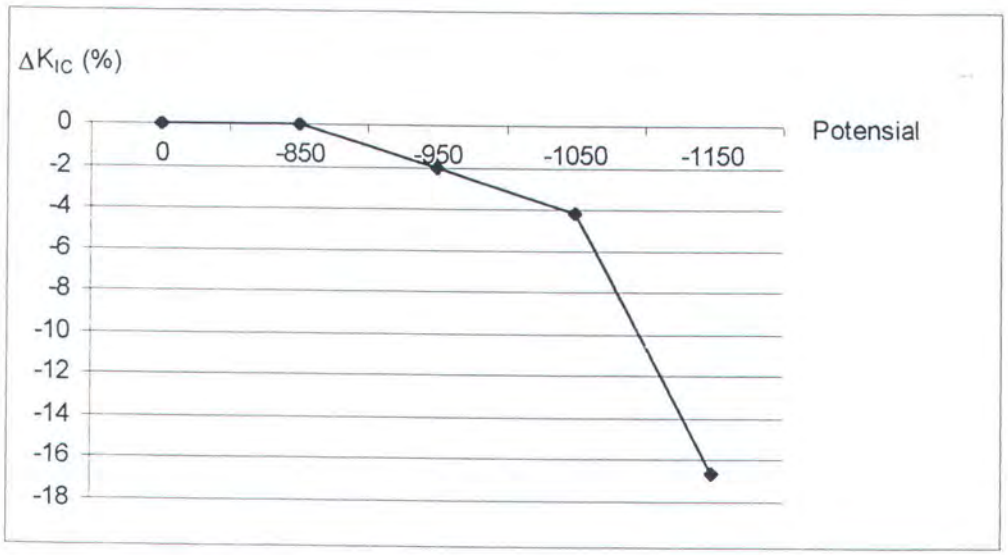
Hasil pengujian *fracture toughness* menunjukkan adanya hubungan antara perubahan potensial yang semakin negatif terhadap ketangguhan material

baja SS-41. Hal ini bisa dilihat dari tabel 5.17 yang menunjukkan prosentase perubahan nilai K_{IC} masing-masing spesimen yang mendapat perlakuan *over protection ICCP* terhadap spesimen yang tidak diberi potensial negatif.

Tabel 5.17. Hubungan antara potensial dengan perubahan harga K_{IC}.

Potensial (mV SCC)	**Δ K_{IC} rata-rata** (%)
0	0
-850	0
-950	-2.08
-1050	-4.17
-1150	-16.67

Dalam sajian grafik, prosentase perubahan tersebut dapat dilihat pada gambar berikut :



Gambar 5.12 Hubungan nilai potensial negatif terhadap prosentase perubahan K_{IC} baja SS 41.

Dari gambar 5.11 terlihat adanya hubungan antara pemberian potensial yang semakin negatif terhadap penurunan nilai K_{IC} baja SS-41. Pada

proses perlindungan katodik dengan *impressed current cathodic protection*, kecepatan reaksi katodik menjadi semakin tinggi yang mempercepat pula terjadinya evolusi hydrogen yang menghasilkan gas hydrogen maupun ion hydrogen yang dapat terdifusi kedalam material.

Penurunan *toughness* material yang diberi potensial negatif seperti yang telihat pada gambar 5.11 diatas dapat dijelaskan sebagai berikut : media utama korosi adalah air (H_2O) yang merupakan molekul netral dan *reversible*, dimana kedua jenis atom yang membentuk molekul air sewaktu-waktu dapat terurai menjadi atom-atom semula. Ion-ion hydrogen yang terbentuk dari proses penguraian air tersebut bergerak mendekati permukaan material uji yang lebih katodik, ion-ion hydrogen ini akan dapat mengikat elektron-elektron yang berada di permukaan logam membentuk atom hydrogen tunggal. Atom hydrogen hanya memiliki satu buah proton sehingga atom hydrogen adalah atom yang paling kecil. Karena sifat hydrogen yang memiliki kecenderungan yang tinggi untuk terserap kedalam atau keluar melalui permukaan material, atom tunggal hydrogen dapat masuk kedalam material uji. Atom tunggal hydrogen adalah bentuk yang tidak stabil, sehingga atom-atom hydrogen yang terkumpul didalam *bulk metal* cenderung untuk mencapai kestabilan dengan membentuk gas hydrogen (H_2).. Dalam bentuk molekul, gas hydrogen tidak dapat terdifusi melalui kisi-kisi logam sehingga tekanan dalam bulk metal akan meningkat. Semakin lama tekanan akan semakin tinggi sehingga dapat mengakibatkan terjadinya gelembung dan timbulnya retak-retak halus pada material, hal ini menurunkan *ductility* yang berarti turunnya ketangguhan (*toughness*) material tersebut.

Semakin tinggi potensial negatif yang diberikan pada proses perlindungan katodik dengan ICCP, semakin cepat reaksi evolusi hydrogen yang terjadi, hal ini berarti semakin banyak hydrogen yang terbentuk sehingga hidrogen yang terdifusi kedalam material semakin banyak. Perbedaan konsentrasi hydrogen yang terbentuk dan terdifusi kedalam material itulah yang menyebabkan adanya perbedaan prosentase penurunan nilai K_{IC} untuk pemberian potensial negatif yang berbeda.

Pemberian potensial negatif yang berlebihan dapat menyebabkan penurunan *fracture toughness* baja SS-41. Pada pengujian ini diperoleh data penurunan ketangguhan antara 2,08 % sampai dengan 16,67 % setelah material baja SS-41 mendapat perlakuan perlindungan korosi metode *impressed current cathodic protection* (ICCP) dengan pemberian potensial negatif yang berlebihan (*over protection*) selama 7 hari (168 jam).

BAB VI

KESIMPULAN DAN SARAN

BAB VI

KESIMPULAN DAN SARAN

6.1 Kesimpulan

Impressed Current Cathodic Protection (ICCP) atau potensial perlindungan katodik arus terpasang adalah salah satu metode perlindungan korosi yang dipakai pada bangunan laut. Prinsip metode ini adalah menjadikan material yang akan dilindungi bertindak sebagai katoda dalam sel korosi dengan memberikan potensial negatif pada material tersebut. Semakin besar potensial negatif yang diberikan maka laju korosi akan semakin berkurang.

Pemberian potensial negatif yang berlebihan (*over protection*) pada baja SS-41 menyebabkan penurunan ketangguhan (*toughness*) material tersebut yang ditunjukkan oleh penurunan nilai *plain strain fracture thoughnes* (K_{IC}) material yang disebabkan adanya *hydrogen damage* pada material.

Penurunan ketangguhan material semakin besar dengan semakin tingginya potensial negatif yang diberikan terhadap material. Penurunan terbesar (16,67 %) terlihat pada pemberian potensial negatif -1150 mV SSC.

6.2 Saran

Fasilitas perlindungan korosi dengan metode *Impressed Current Cathodic Protection* (ICCP) hendaknya dilengkapi dengan peralatan yang dapat mengontrol besarnya potensial perlindungan yang diberikan agar tidak terjadi *over protection* yang bisa memicu terjadinya kegagalan pada struktur.

Perlindungan korosi pada struktur ada yang menggabungkan metode lapisan pelindung (*coating*) dan *Impressed Current Cathodic Protection* (ICCP). Sebagai kelanjutan dari tugas akhir ini, perlu adanya penelitian lebih lanjut untuk mengetahui pengaruh potensial negatif dari ICCP terhadap daya lekat lapisan pelindung.

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LAMPIRAN A

ASTM 8M-85

Standard Methods for
TENSION TESTING OF METALLIC MATERIALS [METRIC][1]

This standard is issued under the fixed designation E 8M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

These methods have been approved for use by agencies of the Department of Defense to replace method 211.1 of Federal Test Method Standard No. 151b and for listing in the DoD Index of Specifications and Standards.

[1] NOTE—Editorial changes were made throughout in March 1986.

1. Scope

1.1 These methods cover the tension testing of metallic materials in any form at room temperature, specifically, the methods of determination of yield strength, yield point, tensile strength, elongation, and reduction of area.

NOTE 1—This specification is the metric companion of Methods E 8.

NOTE 2—These metric methods are essentially the same as those in Methods E 8, and are compatible in technical content except that gage lengths are required to be 5D for most round specimens rather than 4D as specified in Methods E 8.

NOTE 3—Exceptions to the provisions of these methods may need to be made in individual specifications or test methods for a particular material. For examples, see Methods and Definitions A 370 and Methods B 577M.

NOTE 4—Room temperature shall be considered to be 10 to 38°C unless otherwise specified.

1.2 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Applicable Documents

2.1 *ASTM Standards*

A 356 Specification for Heavy-Walled, Carbon, Low Alloy, and Stainless Steel Castings for Steam Turbines[2]

A 370 Methods and Definitions for Mechanical Testing of Steel Products[3]

B 557M Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products [Metric][4]

E 4 Practices for Load Verification of Testing Machines[5]

E 6 Definitions of Terms Relating to Methods of Mechanical Testing[5]

E 29 Recommended Practice for Indicating Which Places of Figures Are to Be Considered Significant in Specified Limiting Values[6]

E 83 Practice for Verification and Classification of Extensometers[5]

E 345 Methods of Tension Testing of Metallic Foil[5]

3. Definitions

3.1 The definitions of terms relating to tension testing appearing in Definitions E 6 shall be considered as applying to the terms used in these methods of tension testing.

4. Significance and Use

4.1 Tension tests provide information on the strength and ductility of materials under uniaxial tensile stresses. This information may be useful in comparisons of materials, alloy development,

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[1] These methods are under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and are the direct responsibility of Subcommittee E28.04 on Tension Testing.

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[2] *Annual Book of ASTM Standards*, Vol 01.02.

[3] *Annual Book of ASTM Standards*, Vol 01.04.

[4] *Annual Book of ASTM Standards*, Vols 02.02 and 03.01.

[5] *Annual Book of ASTM Standards*, Vol 03.01.

[6] *Annual Book of ASTM Standards*, Vols 03.01 and 14.02.

quality control, and design under certain circumstances.

4.2 The results of tension tests of specimens machined to standardized dimensions from selected portions of a part or material may not totally represent the strength and ductility properties of the entire end product or its in-service behavior in different environments.

4.3 These methods are considerd satisfactory for acceptance testing of commercial shipments. The methods have been used extensively in the trade for this purpose.

5. Apparatus

5.1 *Testing Machines*—Machines used for tension testing shall conform to the requirements of Practices E 4. The loads used in determining tensile strength, yield strength, or yield point shall be within the verified loading range of the testing machine as defined in Practices E 4.

5.2 *Gripping Devices:*

5.2.1 *General*—Various types of gripping devices may be used to transmit the measured load applied by the testing machine to the test specimens. To ensure axial tensile stress within the gage length, the axis of the test specimen should coincide with the center line of the heads of the testing machine. Any departure from this requirement may introduce bending stresses that are not included in the usual stress computation (load divided by cross-sectional area).

NOTE 5—The effect of this eccentric loading may be illustrated by calculating the bending moment and stress thus added. For a standard 12.5-mm diameter specimen, the stress increase is 1.5 % for each 0.025 mm of eccentricity. This error increases to about 2.5 %/0.025 mm for a 9-mm diameter specimen and to about 3.2 %/0.025 mm for a 6-mm diameter specimen.

5.2.2 *Wedge Grips*—Testing machines usually are equipped with wedge grips. These wedge grips generally furnish a satisfactory means of gripping long specimens of ductile metal and flat plate test specimens such as those shown in Fig. 1. If, however, for any reason, one grip of a pair advances farther than the other as the grips tighten, an undesirable bending stress may be introduced. When liners are used behind the wedges, they must be of the same thickness and their faces must be flat and parallel. For best results, the wedges should be supported over their entire lengths by the heads of the testing machine. This requires that liners of several thicknesses be available to cover the range of specimen thickness. For proper gripping, it is desirable that the entire length of the serrated face of each wedge be in contact with the specimen. Proper alignment of wedge grips and liners is illustrated in Fig. 2. For short specimens and for specimens of many materials, it is generally necessary to use machined test specimens and to use a special means of gripping to ensure that the specimens, when under load, shall be as nearly as possible in uniformly distributed pure axial tension (see 5.2.3, 5.2.4, and 5.2.5).

5.2.3 *Grips for Threaded and Shouldered Specimens and Brittle Materials*—A schematic diagram of a gripping device for threaded-end specimens is shown in Fig. 3, while Fig. 4 shows a device for gripping specimens with shouldered ends. Both of these gripping devices should be attached to the heads of the testing machine through properly lubricated spherical-seated bearings. The distance between spherical bearings should be as great as feasible.

5.2.4 *Grips for Sheet Materials*—The self-adjusting grips shown in Fig. 5 have proved satisfactory for testing sheet materials that cannot be tested satisfactorily in the usual type of wedge grips.

5.2.5 *Grips for Wire*—Grips of either the wedge or snubbing types as shown in Figs. 5 and 6 or flat wedge grips may be used.

5.3 *Dimension-Measuring Devices*—Micrometers and other devices used for measuring linear dimensions shall be accurate and precise to at least one half the smallest unit to which the individual dimension is required to be measured.

6. Test Specimens

6.1 *General:*

6.1.1 Test specimens shall be either substantially full-size or machined, as prescribed in the product specifications for the material being tested.

6.1.2 Improperly prepared test specimens often are the reason for unsatisfactory and incorrect test results. It is important, therefore, that care be exercised in the preparation of specimens, particularly in the machining, to assure the desired precision and bias in test results.

6.1.3 It is desirable to have the cross-sectional area of the specimen smallest at the center of the reduced section to ensure fracture within the gage length. For this reason, a small taper is permitted in the reduced section of each of the specimens

described in the following sections.

6.1.4 For brittle materials it is desirable to have fillets of large radius at the ends of the gage length.

6.2 *Plate-Type Specimens*—The standard plate-type specimen is shown in Fig. 1. This specimen is used for testing metallic materials in the form of plate, shapes, and flat material having a nominal thickness of 5 mm or over. When product specifications so permit, other types of specimens may be used, as provided in 6.3, 6.4, and 6.5.

6.3 *Sheet-Type Specimens:*

6.3.1 The standard sheet-type test specimen is shown in Fig. 1. This specimen is used for testing metallic materials in the form of sheet, plate, flat wire, strip, band, hoop, rectangles, and shapes ranging in nominal thickness from 0.13 to 16 mm. When product specifications so permit, other types of specimens may be used as provided in 6.2, 6.4, and 6.5.

NOTE 6—Methods E 345 may be used for tension testing of materials in thicknesses up to 0.150 mm.

6.3.2 Pin ends as shown in Fig. 7 may be used. In order to avoid buckling in tests of thin- and high-strength materials, it may be necessary to use stiffening plates at the grip ends.

6.4 *Round Specimens:*

6.4.1 The standard 12.5-mm diameter round test specimen shown in Fig. 8 is used quite generally for testing metallic materials, both cast and wrought.

6.4.2 Figure 8 also shows small-size specimens proportional to the standard specimen. These may be used when it is necessary to test material from which the standard specimen or specimens shown in Fig. 1 cannot be prepared. Other sizes of small, round specimens may be used. In any such small-size specimen, it is important that the gage length for measurement of elongation be five times the diameter of the specimen.

6.4.3 The shape of the ends of the specimen outside of the gage length shall be suitable to the material and of a shape to fit the holders or grips of the testing machine so that the loads may be applied axially. Figure 9 shows specimens with various types of ends that have given satisfactory results.

6.5 *Specimens for Sheet, Plate, Flat Wire, and Strip*—In testing sheet, plate, flat wire, and strip one of the following types of specimens shall be used:

6.5.1 For material ranging in nominal thickness from 0.13 to 16 mm, use the sheet-type specimen described in 6.3.

NOTE 7—Attention is called to the fact that either of the flat specimens described in 6.2 and 6.3 may be used for material from 5 to 16 mm in thickness, and one of the round specimens described in 6.4 may also be used for material 12.5 mm or more in thickness.

6.5.2 For material having a nominal thickness of 5 mm or over (Note 7), use the plate-type specimen described in 6.2.

6.5.3 For material having a nominal thickness of 12.5 mm or over (Note 7), use the largest practical size of specimen described in 6.4.

6.6 *Specimens for Wire, Rod, and Bar:*

6.6.1 For round wire and rod, test specimens having the full cross-sectional area of the wire or rod shall be used wherever practicable. The gage length for the measurement of elongation of wire less than 4 mm in diameter shall be as prescribed in product specifications. In testing wire which has a 4 mm or larger diameter, unless otherwise specified, a gage length five times the diameter (rounded to the nearest 5 mm) or greater shall be used. The total length of the specimens shall be at least equal to the gage length plus the length of wire required for the full use of the grips employed.

6.6.2 For wire of octagonal, hexagonal, or square cross section, for rod or bar of round cross section where the specimen required in 6.6.1 is not practicable, and for rod or bar of octagonal, hexagonal, or square cross section, one of the following types of specimens shall be used:

6.6.2.1 *Full Cross Section* (Note 8)—It is permissible to reduce the test section slightly with abrasive cloth or paper, or machine it sufficiently to ensure fracture within the gage marks. For material not exceeding 5 mm in diameter or distance between flats, the cross-sectional area may be reduced to not less than 90 % of the original area without changing the shape of the cross section. For material over 5 mm in diameter or distance between flats, the diameter or distance between flats may be reduced by not more than 0.25 mm without changing the shape of the cross section. Square, hexagonal, or octagonal wire or rod not exceeding 5 mm between flats may be turned to a round having a cross-sectional area not smaller than 90 % of the area of the maximum inscribed circle. Fillets, preferably with a radius of 10 mm, but not less than 3 mm, shall be used at the ends of the reduced

sections. Square, hexagonal, or octagonal rod over 5 mm between flats may be turned to a round having a diameter no smaller than 0.25 mm less than the original distance between flats.

NOTE 8—The ends of copper or copper alloy specimens may be flattened 10 to 50 % from the original dimension in a jig similar to that shown in Fig. 10, to facilitate fracture within the gage marks. In flattening the opposite ends of the test specimen, care shall be taken to ensure that the four flattened surfaces are parallel and that the two parallel surfaces on the same side of the axis of the test specimen lie in the same plane.

6.6.2.2 For rod and bar, the largest practical size of round specimen as described in 6.4 may be used in place of a test specimen of full cross section. Unless otherwise specified in the product specification, specimens shall be parallel to the direction of rolling or extrusion.

6.7 *Specimens for Rectangular Bar*—In testing rectangular bar one of the following types of specimens shall be used:

6.7.1 *Full Cross Section*—It is permissible to reduce the width of the specimen throughout the test section with abrasive cloth or paper, or by machining sufficiently to facilitate fracture within the gage marks, but in no case shall the reduced width be less than 90 % of the original. The edges of the midlength of the reduced section not less than 20 mm in length shall be parallel to each other and to the longitudinal axis of the specimen within 0.05 mm. Fillets, preferably with a radius of 10 mm but not less than 3 mm, shall be used at the ends of the reduced sections.

6.7.2 Rectangular bars of thickness small enough to fit the grips of the testing machine but of too great width may be reduced in width by cutting to fit the grips, after which the cut surfaces shall be machined or cut and smoothed to ensure failure within the desired section. The reduced width shall be not less than the original bar thickness. Also, one of the types of specimens described in 6.2, 6.3, and 6.4 may be used.

6.8 *Shapes, Structural and Other*—In testing shapes other than those covered by the preceding sections, one of the types of specimens described in 6.2, 6.3, and 6.4 shall be used.

6.9 *Specimens for Pipe and Tube:*

6.9.1 The term "tube" is used to indicate tubular products in general, and includes pipe, tube, and tubing.

6.9.2 For small tube, particularly sizes 25 mm and under in nominal outside diameter, and frequently for larger sizes, except as limited by the testing equipment, it is standard practice to use tension test specimens of full-size tubular sections. Snug-fitting metal plugs shall be inserted far enough into the ends of such tubular specimens to permit the testing machine jaws to grip the specimens properly. The plugs shall not extend into that part of the specimen on which the elongation is measured. Figure 11 shows a suitable form of plug, the location of the plugs in the specimen, and the location of the specimen in the grips of the testing machine.

6.9.3 For large-diameter tube that cannot be tested in full section, longitudinal tension test specimens shall be cut as indicated in Fig. 12. Specimens from welded tube shall be located approximately 90° from the weld. If the tube-wall thickness is under 20 mm, either a specimen of the form and dimensions shown in Fig. 13 or one of the small-size specimens proportional to the standard 12.5-mm specimen, as mentioned in 6.4.2 and shown in Fig. 8, shall be used. Specimens of the type shown in Fig. 13 may be tested with grips having a surface contour corresponding to the curvature of the tube. When grips with curved faces are not available, the ends of the specimens may be flattened without heating. If the tube-wall thickness is 20 mm or over, the standard specimen shown in Fig. 8 shall be used.

6.9.4 Transverse tension test specimens for tube may be taken from rings cut from the ends of the tube as shown in Fig. 14. Flattening of the specimen may be either after separating as in *A*, or before separating as in *B*. Transverse tension test specimens for large tube under 20 mm in wall thickness shall be either of the small-size specimens shown in Fig. 8 or of the form and dimensions shown for Specimen 2 in Fig. 13. When using the latter specimen, either or both surfaces of the specimen may be machined to secure a uniform thickness, provided not more than 15 % of the normal wall thickness is removed from each surface. For large tube 20 mm and over in wall thickness, the standard specimen shown in Fig. 8 shall be used for transverse tension tests. Specimens for transverse tension tests on large welded tube to determine the strength of welds shall be located perpendicular to the welded seams, with the welds at about the middle of their lengths.

6.10 *Specimens for Forgings*—For testing forgings, the largest round specimen described in 6.4 shall be used. If round specimens are not

feasible, then the largest specimen described in 6.5 shall be used.

6.11 *Specimens for Castings*—In testing castings either the standard specimen shown in Fig. 8 or the specimen shown in Fig. 15 shall be used unless otherwise provided in the product specifications.

6.11.1 Test coupons for castings shall be made as shown in Fig. 16 and Table 1.

6.12 *Specimen for Malleable Iron*—For testing malleable iron the test specimen shown in Fig. 17 shall be used, unless otherwise provided in the product specifications.

6.13 *Specimen for Die Castings*—For testing die castings the test specimen shown in Fig. 18 shall be used unless otherwise provided in the product specifications.

6.14 *Specimens for Powdered Metals*—For testing powdered metals the test specimens shown in Figs. 19 and 20 shall be used, unless otherwise provided in the product specifications.

6.15 *Gage Length of Test Specimens*—The gage length for the determination of elongation shall be in accordance with the product specifications for the material being tested. Gage marks shall be stamped lightly with a punch, scribed lightly with dividers or drawn with ink as preferred. For material that is sensitive to the effect of slight notches and for small specimens, the use of layout ink will aid in locating the original gage marks after fracture.

6.16 *Location of Test Specimens:*

6.16.1 Unless otherwise specified, the axis of the test specimen shall be located as follows:

6.16.1.1 At the center for products 40 mm or less in thickness, diameter, or distance between flats.

6.16.1.2 Midway from the center to the surface for products over 40 mm in thickness, diameter, or distance between flats.

6.16.2 For forgings, specimens shall be taken as provided in the applicable product specifications, either from the predominant or thickest part of the forging from which a coupon can be obtained, or from a prolongation of the forging, or from separately forged coupons representative of the forging. When not otherwise specified, the axis of the specimen shall be parallel to the direction of grain flow.

6.17 *Surface Finish of Specimens*—When materials are tested with surface conditions other than as manufactured, the surface finish of the test specimens shall be as provided in the applicable product specifications.

NOTE 9—Particular attention should be given to the uniformity and quality of surface finishes of specimens for high strength and very low ductility materials since this has been shown to be a factor in the variability of test results.

7. Procedures

7.1 *Measurement of Dimensions of Test Specimens:*

7.1.1 To determine the cross-sectional area of a test specimen, measure the dimensions of the cross section at the center of the reduced section. For referee testing of specimens under 5 mm in their least dimension, measure the dimensions where the least cross-sectional area is found. Measure and record the cross-sectional dimensions of tension test specimens 5 mm and over to the nearest 0.02 mm; the cross-sectional dimensions less than 5 mm and not less than 2.5 mm to the nearest 0.01 mm; the cross-sectional dimensions less than 2.5 mm and not less than 0.50 mm to the nearest 0.002 mm: and when practical, the cross-sectional dimensions less than 0.50 mm to at least the nearest 1 % but in all cases to at least the nearest 0.002 mm.

NOTE 10—Measurements of dimensions presume smooth surface finishes for the specimens. Rough surfaces due to the manufacturing process such as hot rolling, metallic coating, etc., may lead to inaccuracy of the computed areas greater than the measured dimensions would indicate. Therefore, cross-sectional dimensions of tension test specimens with rough surfaces due to processing may be measured and recorded to the nearest 0.02 mm.

7.1.2 Determine cross-sectional areas of full-size test specimens of nonsymmetrical cross sections by weighing a length not less than 20 times the largest cross-sectional dimension and using the value of density of the material. Determine the mass to the nearest 0.5 % or less.

7.1.3 When using specimens of the type shown in Fig. 13 taken from tubes, the cross-sectional area shall be determined as follows:

If $D/W \leq 6$:

$$A = [(W/4) \times (D^2 - W^2)^{1/2}] + [(D^2/4) \times \arcsin(W/D)] - [(W/4) \times ((D - 2T)^2 - W^2)^{1/2}] - [((D - 2T)/2)^2 \times \arcsin(W/(D - 2T))]$$

where:

A = exact cross-sectional area, mm^2,

W = width of the specimen in the reduced section, mm,

D = measured outside diameter of the tube, mm, and
T = measured wall thickness of the specimen, mm.

arcsin values to be in radians

If $D/W > 6$, the exact equation or the following equation may be used:

$$A = W \times T$$

where:

A = approximate cross-sectional area, mm^2,
W = width of the specimen in the reduced section, mm, and
T = measured wall thickness of the specimen, mm.

7.2 *Speed of Testing:*

7.2.1 Speed of testing may be defined (*a*) in terms of rate of straining the specimen, (*b*) in terms of rate of stressing the specimen, (*c*) in terms of the elapsed time for completing part or all of the test, (*d*) in terms of rate of separation of the two heads of the testing machine during a test, or (*e*) in terms of free-running crosshead speed (rate of movement of the crosshead of the testing machine when not under load).

NOTE 11—For some materials, the free-running crosshead speed, which is the least accurate, may be adequate, while for other materials one of the others, listed in decreasing order of precision, may be necessary in order to obtain test values within acceptable limits.

7.2.1.1 Specifying suitable numerical limits for speed and selection of the method are the responsibilities of the product committees. Suitable limits for speed of testing should be specified for materials for which the differences resulting from the use of different testing speeds are of such magnitude that the test results are unsatisfactory for determining the acceptability of the material. In such instances, depending upon the material and the use for which the test results are intended, one or more of the methods described in the following paragraphs is recommended for specifying speed of testing.

NOTE 12—Speed of testing can affect test values because of the rate sensitivity of materials and the temperature-time effects.

7.2.2 *Rate of Straining*—The allowable limits for rate of straining shall be specified in millimetres displacement per millimetre of gage length per second (gage length could be the distance between grips or the length of reduced section). Some testing machines are equipped with pacing or indicating devices for the measurement and control of rate of straining, but in the absence of such a device the average rate of straining shall be determined with a timing device by observing the time required to effect a known increment of strain.

7.2.3 *Rate of Stressing*—The allowable limits for rate of stressing shall be specified in megapascals per second. Many testing machines are equipped with pacing or indicating devices for the measurement and control of the rate of stressing, but in the absence of such a device the average rate of stressing shall be determined with a timing device by observing the time required to apply a known increment of stress.

7.2.4 *Elapsed Time*—The allowable limits for the elapsed time from the beginning of loading (or from some specified stress) to the instant of fracture, to the maximum load, or to some other stated stress, shall be specified in seconds. The elapsed time can be determined with a timing device.

7.2.5 *Free-Running Crosshead Speed*—The allowable limits for the rate of movement of the crosshead of the testing machine, when not under load, shall be specified in millimetres per second. The limits for the crosshead speed may be further qualified by specifying different limits for various types and sizes of specimens. The average crosshead speed shall be experimentally determined by using length-measuring and timing devices.

7.2.6 *Rate of Separation of Heads During Tests*—The allowable limits for rate of separation of the heads of the testing machine during a test shall be specified in millimetres per millimetre of length of reduced section (or distance between grips for specimens not having reduced sections) per second. The limits for the rate of separation may be further qualified by specifying different limits for various types and sizes of specimens. Many testing machines are equipped with pacing or indicating devices for the measurement and control of the rate of separation of the heads of the machine during a test, but in the absence of such a device the average rate of separation of the heads shall be experimentally determined by using length-measuring and timing devices.

7.2.7 Unless otherwise specified, any convenient speed of testing may be used up to one half the specified yield strength or yield point, or up to one quarter the specified tensile strength, whichever is smaller. The speed above this point shall be within the limits specified. If different

speed limitations are required for use in determining yield strength, yield point, tensile strength, elongation, and reduction of area, they should be stated in the product specifications. In the absence of any specified limitations on speed of testing the following general rules apply:

7.2.7.1 The speed of testing shall be such that the loads and strains used in obtaining the test results are accurately indicated.

7.2.7.2 During the conduct of the test to determine yield strength or yield point the rate of stress application shall not exceed 12 MPa/s.

7.2.7.3 After the yield strength or yield point has been determined, the speed may be increased to correspond to a maximum strain rate of 0.01 mm/mm/s. The extensometer and strain rate indicator may be used to set the strain rate prior to its removal. If the extensometer and strain rate indicator are not used to set this strain rate, the speed should be set not to exceed 0.01 mm/mm of the length of the reduced section (or distance between the grips for specimens not having reduced sections) per second.

7.3 *Determination of Yield Strength*—Determine yield strength by either of the methods described in 7.3.1 or 7.3.2.

7.3.1 *Offset Method*—To determine the yield strength by the "offset method," it is necessary to secure data (autographic or numerical) from which a stress-strain diagram may be drawn. Then on the stress-strain diagram (Fig. 21) lay off *Om* equal to the specified value of the "offset," draw *mn* parallel to *OA*, and thus locate *r*, the intersection of *mn* with the stress-strain diagram (Note 13). In reporting values of yield strength obtained by this method, the specified value of offset used should be stated in parentheses after the term yield strength.
Thus:

Yield strength (offset = 0.2 %) = 360 MPa

In using this method a Class B2 extensometer (see Practice E 83) would be sufficiently sensitive for most materials.

7.3.2 *Extension-Under-Load Method*—To determine the yield strength by the extension-under-load (EUL) method, it is necessary to secure data as follows: (*1*) by autographic or numerical devices so that a stress-strain (or load-elongation) diagram may be drawn from which the value of the stress occurring at the specified value of extension may be ascertained; or (*2*) by a device attached to or part of an extensometer that indicates when the specified extension occurs so that the stress then occurring may be ascertained—either or both the devices attached to the extensometer or the load-indicating device may be automatic. This method is illustrated in Fig. 22. The extension can be satisfactorily determined by the use of a Class B2 extensometer (see Practice E 83). The stress that occurs at the specified extension shall be reported thus:

Yield strength (EUL = *XX*) = *ZZ* MPa

where *XX* is the specified value of extension.

NOTE 13—If the load drops before the specified offset or extension-under-load is reached, technically the material does not have a yield strength (for that offset or extension-under-load), but the stress at the maximum load before the specified offset or extension-under-load is reached may be reported instead of the yield strength.

NOTE 14—When there is disagreement over the results of this test, the offset method for determining yield strength is recommended as the referee method.

7.4 *Determination of Yield Point:*

7.4.1 For materials that exhibit discontinuous yielding, detemine the yield point by either of the methods described in 7.4.1.1 or 7.4.1.2.

7.4.1.1 *Autographic Diagram Method*—Obtain a stress-strain (or load elongation) diagram by an autographic device, and record the stress corresponding to the top of the knee or the point at which the curve drops as the yield point. This method is illustrated in Fig. 23.

7.4.1.2 *Extension-Under-Load Method*—To determine the yield point by the extension-under-load (EUL) method, it is necessary to secure data as follows: (*1*) by autographic or numerical devices so that a stress-strain diagram may be drawn from which the value of the stress occurring at the specified value of extension may be ascertained; or (*2*) by a device attached to or part of an extensometer that indicates when the specified extension occurs so that the load then occurring may be ascertained—either or both the devices attached to the extensometer or the load-indicating device may be automatic. This method is illustrated in Fig. 22. The extension can be satisfactorily determined by the use of a Class C extensometer. The stress that occurs at the specified extension shall be reported as the yield point.

NOTE 15—The appropriate value of the total extension should be specified. For steel with yield point specified not over 550 MPa, an appropriate value is 0.005 mm/mm of gage length. For higher strength

steels, yield strength should be specified in preference to yield point.

7.4.2 *Halt-of-the-Load Method*—Apply an increasing load to the specimen at a uniform deformation rate. When the yield point of the material is reached, the increase of the load stops. At that time, there is a halt or hesitation of the load-indicating mechanism. When the increase in load stops or hesitates, record the corresponding stress as the yield point.

NOTE 16—This method was formerly known as the halt-of-the-pointer method and also as the drop-of-the-beam method.

7.5 *Tensile Strength*—Calculate the tensile strength by dividing the maximum load carried by the specimen during a tension test by the original cross-sectional area of the specimen.

7.6 *Elongation:*

7.6.1 In reporting values of elongation, give both the original gage length and the percentage increase.

Example: elongation
= 30 % increase (50-mm gage length)

7.6.2 When the specified elongation is greater than 3 %, fit ends of the fractured specimen together carefully and measure the distance between the gage marks to the nearest 0.25 mm for gage lengths of 50 mm and under, and to at least the nearest 0.5 % of the gage length for gage lengths over 50 mm. A percentage scale reading to 0.5 % of the gage length may be used.

7.6.3 When the *specified* elongation is 3 % or less, determine the elongation of standard round specimens (see Fig. 8) using the following procedure, except that the procedure given in 7.6.2 may be used instead when the *measured* elongation is greater than 3 %.

7.6.3.1 Measure the original gage length of the specimen to the nearest 0.05 mm.

7.6.3.2 Remove partly torn fragments that will interfere with fitting together the ends of the fractured specimen or with making the final measurement.

7.6.3.3 Fit the fractured ends together with matched surfaces and apply an end load along the axis of the specimen sufficient to close the fractured ends together. If desired, this load may then be removed carefully, provided the specimen remains intact.

NOTE 17—The use of an end load of approximately 15 MPa has been found to give satisfactory results on test specimens of aluminum alloy.

7.6.3.4 Measure the final gage length to the nearest 0.05 mm and report the elongation to the nearest 0.2 %.

7.6.4 Specimens other than the standard specimen described in Fig. 8 are exempt from the requirements of 7.6.3 except as required by the applicable product specification.

7.6.5 If any part of the fracture takes place outside of the middle half of the gage length or in a punched or scribed mark within the reduced section, the elongation value obtained may not be representative of the material. In acceptance testing, if the elongation so measured meets the minimum requirements specified, no further testing is required, but if the elongation is less than the minimum requirements, discard the test and retest.

7.6.6 In determining extension at fracture (elastic plus plastic extension), autographic or automated methods using extensometers may be employed.

7.6.6.1 In determining percent elongation from extension at fracture data, only the plastic extension shall be used. The elastic portion can be estimated graphically or by calculation, and then subtracted from the total extension at fracture.

7.7 *Reduction of Area:*

7.7.1 *Specimens With Originally Circular Cross Sections*—Fit the ends of the fractured specimen together and measure the reduced diameter to the same accuracy as the original measurement.

NOTE 18—Because of anisotropy, circular cross sections often do not remain circular during straining in tension. The shape is usually elliptical, thus, the area may be calculated by $\pi \cdot d_1 \cdot d_2/4$, where d_1 and d_2 are the major and minor diameters, respectively.

7.7.2 *Specimens With Originally Rectangular Cross Sections*—Fit the ends of the fractured specimen together and measure the thickness and width at the minimum cross section to the same accuracy as the original measurements.

NOTE 19—Because of the constraint to deformation that occurs at the corners of rectangular specimens, the dimensions at the center of the original flat surfaces are less than those at the corners. The shape of these surfaces are often assumed to be parabolic. When this assumption is made, an effective thickness, t_e, may be calculated by: $(t_1+4t_2+t_3)/6$, where t_1 and t_3 are the thicknesses at the corners, and t_2 is the thickness at the mid-width. An effective width may be similarly calculated.

7.7.3 Calculate the reduced area based upon

the dimensions determined in 7.7.1 or 7.7.2. The difference between the area thus found and the area of the original cross section expressed as a percentage of the original area, is the reduction of area.

7.7.4 If any part of the fracture takes place outside the middle half of the reduced section or in a punched or scribed gage mark within the reduced section, the reduction of area value obtained may not be representative of the material. In acceptance testing, if the reduction of area so calculated meets the minimum requirements specified, no further testing is required, but if the reduction of area is less than the minimum requirements, discard the test results and retest.

7.8 *Rounding Reported Test Data for Yield Strength, Yield Point, and Tensile Strength:*

7.8.1 Test data should be rounded using the procedures of Recommended Practice E 29 and the specific procedures in the product specifications. In the absence of a specified procedure for rounding the test data, one of the procedures described in the following paragraphs is recommended.

7.8.2 For test values up to 500 MPa, round to the nearest 1 MPa; for test values of 500 MPa and up to 1000 MPa, round to the nearest 5 MPa; for test values of 1000 MPa and greater, round to the nearest 10 MPa.

NOTE 20—For steel products, see Methods and Definitions A 370.

7.8.3 For all test values, round to the nearest 0.5 MPa.

NOTE 21—For aluminum- and magnesium-alloy products, see Methods B 557M.

7.8.4 For all test values, round to the nearest 5 MPa.

7.9 *Replacement of Specimens*—A test specimen may be discarded and a replacement specimen selected from the same lot of material in the following cases:

7.9.1 The original specimen had a poorly machined surface,

7.9.2 The original specimen had the wrong dimensions,

7.9.3 The specimen's properties were changed because of poor machining practice,

7.9.4 The test procedure was incorrect,

7.9.5 The fracture was outside the gage length,

7.9.6 For elongation determinations, the fracture was outside the middle half of the gage length, or

7.9.7 There was a malfunction of the testing equipment.

NOTE 22—The tension specimen is inappropriate for assessing some types of imperfections in a material. Other methods and specimens employing ultrasonics, dye penetrants, radiography, etc., may be considered when flaws such as cracks, flakes, porosity, etc., are revealed during a test and soundness is a condition of acceptance.

8. Report

8.1 Test information to be reported shall include the following when applicable:

8.1.1 Material and sample identification.

8.1.2 Yield strength and the method used to determine yield strength (see 7.3).

8.1.3 Yield point and the method used to determine yield point (see 7.4).

8.1.4 Tensile strength (see 7.5).

8.1.5 Elongation (report both the original gage length and the percentage increase) (see 7.6).

8.1.6 Reduction of area (see 7.7).

8.2 Test information to be available on request shall include:

8.2.1 Specimen type (Section 6).

8.2.2 Specimen test section dimension(s).

8.2.3 Formula used to calculate cross-sectional area of specimens taken from large-diameter tubular products.

8.2.4 Speed and method used to determine speed of testing (see 7.2).

8.2.5 Method used for rounding of test results (see 7.8).

8.2.6 Reasons for replacement specimens (see 7.9).

9. Precision and Bias[7]

9.1 *Precision*—The precision of these methods is being established.

9.2 *Bias*—The bias of these methods includes quantitative estimates of the uncertainties of the dimensional measuring devices, the calibrations of test equipment, and the skill of the operators. At this time, statements on bias should be limited to the documented performance of particular laboratories.

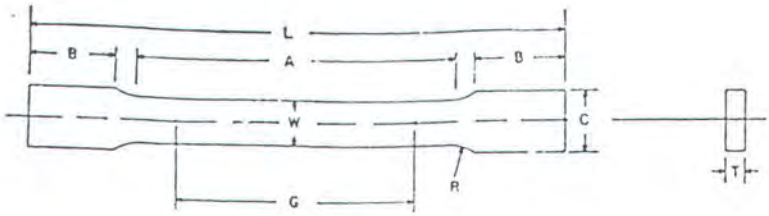
[7] Supporting data available on loan from ASTM Headquarters. Request RR: E28-1004 and E28-1006.

TABLE 1 Details of Test Coupon Design for Castings (See Fig. 16)

NOTE 1—*Test Coupons for Large and Heavy Steel Castings:* The test coupons in Fig. 16 are to be used for large and heavy steel castings. However, at the option of the foundry the cross-sectional area and length of the standard coupon may be increased as desired. This provision does not apply to Specification A 356.

NOTE 2—*Bend Bar:* If a bend bar is required, an alternate design (as shown by dotted lines in Fig. 16) is indicated.

Log Design (125 mm)		Riser Design	
1. *L* (length)	A 125-mm minimum length will be used. This length may be increased at the option of the foundry to accommodate additional test bars (see Note 1).	1. *L* (length)	The length of the riser at the base will be the same as the top length of the leg. The length of the riser at the top therefore depends on the amount of taper added to the riser.
2. End taper	Use of and size of end taper is at the option of the foundry.	2. Width	The width of the riser at the base of a multiple-leg coupon shall be *n* (57 mm) − 16 mm where *n* equals the number of legs attached to the coupon. The width of the riser at the top is therefore dependent on the amount of taper added to the riser.
3. Height	32 mm		
4. Width (at top)	32 mm (see Note 1).		
5. Radius (at bottom)	13 mm max		
6. Spacing between legs	A 13-mm radius will be used between the legs.		
7. Location of test bars	The tensile, bend, and impact bars will be taken from the lower portion of the leg (see Note 2).		
8. Number of legs	The number of legs attached to the coupon is at the option of the foundry providing they are equispaced according to Item 6.	3. *T* (riser taper)	Use of and size is at the option of the foundry.
		Height	The minimum height of the riser shall be 51 mm. The maximum height is at the option of the foundry for the following reasons: (*a*) many risers are cast open, (*b*) different compositions may require variation in risering for soundness, or (*c*) different pouring temperatures may require variation in risering for soundness.
9. R_1	Radius from 0 to approximately 2 mm		



Dimensions, mm

Nominal Width	Standard Specimens		Subsize Specimen
	Plate-Type 40 mm	Sheet-Type 12.5 mm	6 mm
G— Gage length (Notes 1 and 2)	200.0 ± 0.2	50.0 ± 0.1	25.0 ± 0.1
W— Width (Notes 3 and 4)	40.0 ± 2.0	12.5 ± 0.2	6.0 ± 0.1
T— Thickness (Note 5)		thickness of material	
R— Radius of fillet, min (Note 6)	25	12.5	6
L— Overall length, min (Notes 2 and 7)	450	200	100
A— Length of reduced section, min	225	57	32
B— Length of grip section, min (Note 8)	75	50	30
C— Width of grip section, approximate (Notes 4 and 9)	50	20	10

NOTE 1—For the 40-mm wide specimen, punch marks for measuring elongation after fracture shall be made on the flat or on the edge of the specimen and within the reduced section. Either a set of nine or more punch marks 25 mm apart, or one or more pairs of punch marks 200 mm apart, may be used.

NOTE 2—When elongation measurements of 40-mm wide specimens are not required, a minimum length of reduced section (*A*) of 75 mm may be used with all other dimensions similar to the plate-type specimen.

NOTE 3—For the three sizes of specimens, the ends of the reduced section shall not differ in width by more than 0.10, 0.05 or 0.02 mm, respectively. Also, there may be a gradual decrease in width from the ends to the center, but the width at each end shall not be more than 1 % larger than the width at the center.

NOTE 4—For each of the three sizes of specimens, narrower widths (*W* and *C*) may be used when necessary. In such cases the width of the reduced section should be as large as the width of the material being tested permits; however, unless stated specifically, the requirements for elongation in a product specification shall not apply when these narrower specimens are used.

NOTE 5—The dimension *T* is the thickness of the test specimen as provided for in the applicable material specifications. Minimum thickness of 40-mm wide specimens shall be 5 mm. Maximum thickness of 12.5-mm and 6-mm wide specimens shall be 12.5 mm and 6 mm, respectively.

NOTE 6—For the 40-mm wide specimen, a 13-mm minimum radius at the ends of the reduced section is permitted for steel specimens under 690 MPa in tensile strength when a profile cutter is used to machine the reduced section.

NOTE 7—To aid in obtaining axial loading during testing of 6-mm wide specimens, the overall length should be as large as the material will permit, up to 200 mm.

NOTE 8—It is desirable, if possible, to make the length of the grip section large enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips. If the thickness of 12.5-mm wide specimens is over 10 mm, longer grips and correspondingly longer grip sections of the specimen may be necessary to prevent failure in the grip section.

NOTE 9—For the three sizes of specimens, the ends of the specimen shall be symmetrical in width with the center line of the reduced section within 2.5, 0.25, and 0.13 mm, respectively. However, for referee testing and when required by product specifications, the ends of the 12.5-mm wide specimen shall be symmetrical within 0.2 mm.

NOTE 10—Specimens with sides parallel throughout their length are permitted, except for referee testing, provided: (*a*) the above tolerances are used; (*b*) an adequate number of marks are provided for determination of elongation; and (*c*) when yield strength is determined, a suitable extensometer is used. If the fracture occurs at a distance of less than 2*W* from the edge of the gripping device, the tensile properties determined may not be representative of the material. In acceptance testing, if the properties meet the minimum requirements specified, no further testing is required, but if they are less than the minimum requirements, discard the test and retest.

FIG. 1 **Rectangular Tension Test Specimens**

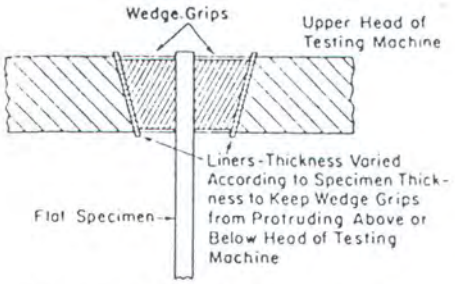


FIG. 2 Wedge Grips with Liners for Flat Specimens

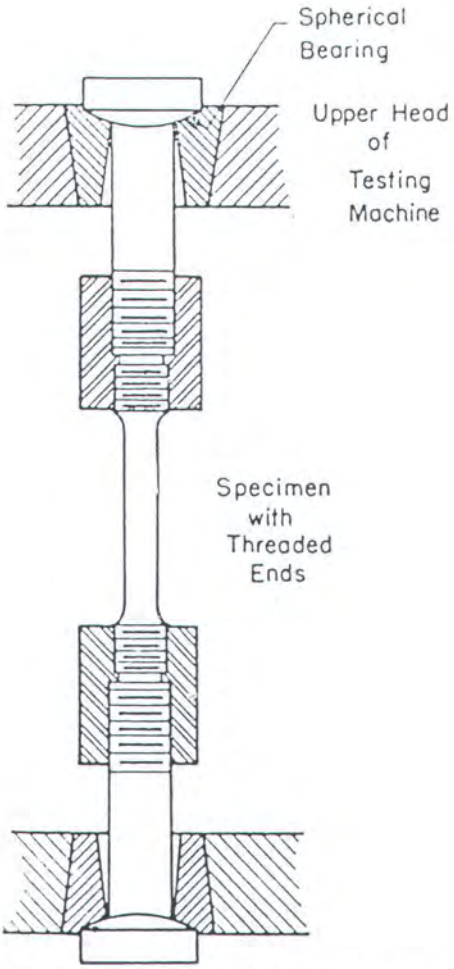


FIG. 3 Gripping Device for Threaded-End Specimens

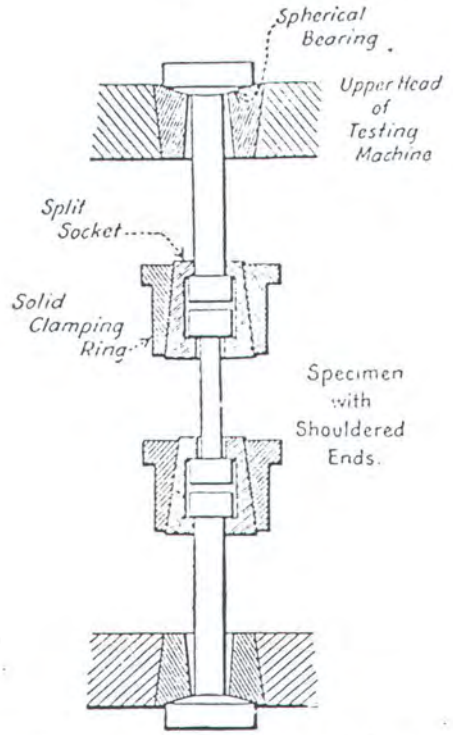


FIG. 4 Gripping Device for Shouldered-End Specimens

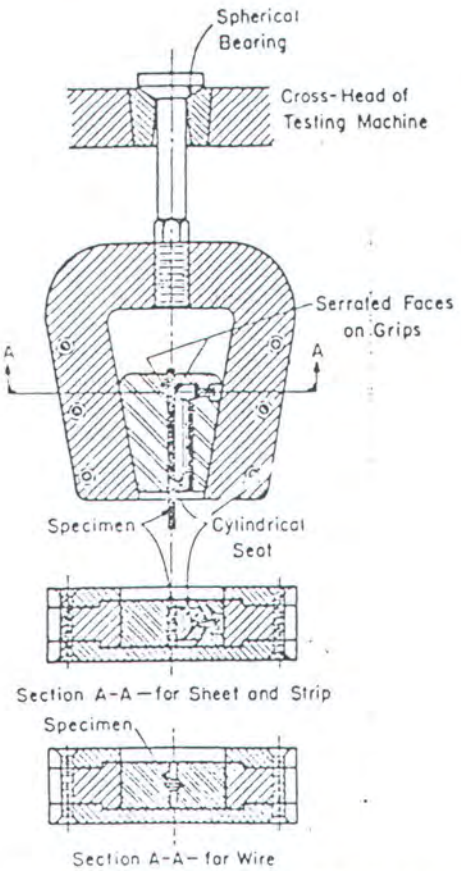


FIG. 5 Gripping Devices for Sheet and Wire Specimens

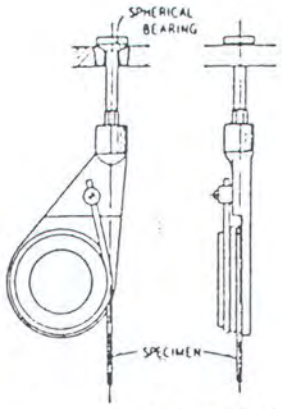
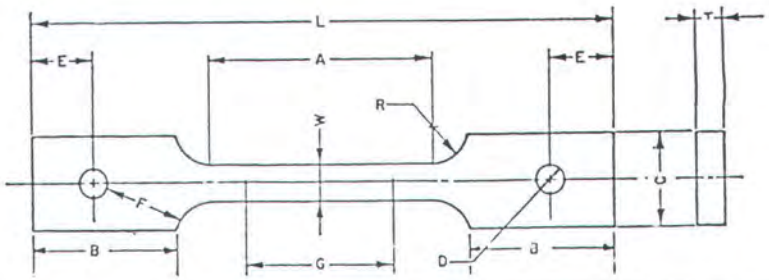


FIG. 6 Snubbing Device for Testing Wire



	Dimensions, mm
G— Gage length	50.0 ± 0.1
W— Width (Note 1)	12.5 ± 0.2
T— Thickness, max (Note 2)	12.5
R— Radius of fillet, min (Note 3)	13
L— Overall length, min	200
A— Length of reduced section, min	57
B— Length of grip section, min	50
C— Width of grip section, approximate	50
D— Diameter of hole for pin, min (Note 4)	13
E— Edge distance from pin, approximate	40
F— Distance from hole to fillet, min	15

NOTE 1—The ends of the reduced section shall differ in width by not more than 0.1 mm. There may be a gradual taper in width from the ends to the center, but the width at each end shall be not more than 1 % greater than the width at the center.

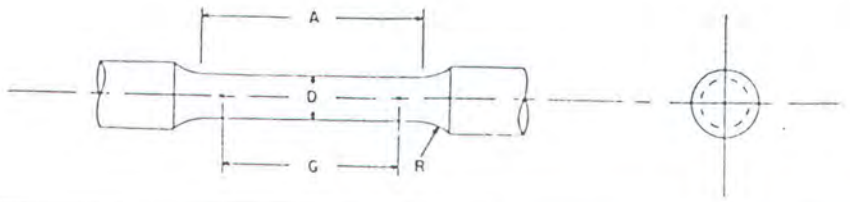
NOTE 2—The dimension *T* is the thickness of the test specimen as stated in the applicable product specifications.

NOTE 3—For some materials, a fillet radius *R* larger than 13 mm may be needed.

NOTE 4—Holes must be on center line of reduced section, within ± 0.1 mm.

NOTE 5—Variations of dimensions *C*, *D*, *E*, *F*, and *L* may be used that will permit failure within the gage length.

FIG. 7 Pin-Loaded Tension Test Specimen with 50-mm Gage Length
Dimensions, mm



	Standard Specimen	Small-Size Specimens Proportional To Standard			
	12.5	9	6	4	2.5
G— Gage length	62.5 ± 0.1	45.0 ± 0.1	30.0 ± 0.1	20.0 ± 0.1	12.5 ± 0.1
D— Diameter (Note 1)	12.5 ± 0.2	9.0 ± 0.1	6.0 ± 0.1	4.0 ± 0.1	2.5 ± 0.1
R— Radius of fillet, min	10	8	6	4	2
A— Length of reduced section, min (Note 2)	75	54	36	24	20

NOTE 1—The reduced section may have a gradual taper from the ends toward the center, with the ends not more than 1 % larger in diameter than the center (controlling dimension).

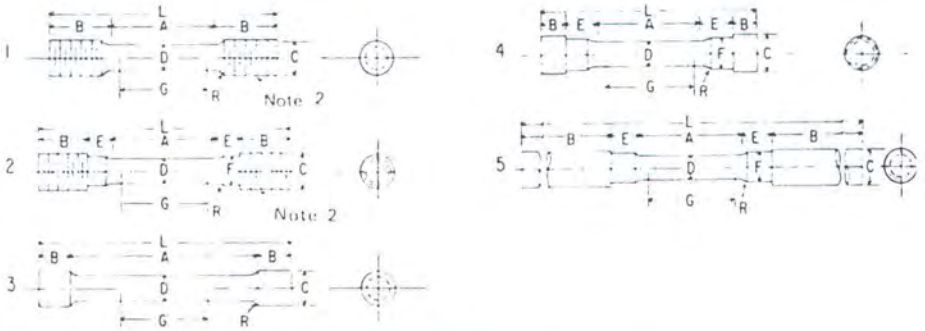
NOTE 2—If desired, the length of the reduced section may be increased to accommodate an extensometer of any convenient gage length. Reference marks for the measurement of elongation should, nevertheless, be spaced at the indicated gage length.

NOTE 3—The gage length and fillets shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the load may be axial (see Fig. 9). If the ends are to be held in wedge grips it is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips.

NOTE 4—On the round specimens in Figs. 8 and 9, the gage lengths are equal to five times the nominal diameter. In some product specifications other specimens may be provided for, but the 5-to-1 ratio is maintained within dimensional tolerances, the elongation values may not be comparable with those obtained from the standard test specimen.

NOTE 5—The use of specimens smaller than 6 mm in diameter shall be restricted to cases when the material to be tested is of insufficient size to obtain larger specimens or when all parties agree to their use for acceptance testing. Smaller specimens require suitable equipment and greater skill in both machining and testing.

FIG. 8 Standard 12.5-mm Round Tension Test Specimen with Gage Lengths Five Times the Diameters (5D), and Examples of Small-Size Specimens Proportional to the Standard Specimen



Dimensions, mm

	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G— Gage length	62.5 ± 0.1	62.5 ± 0.1	62.5 ± 0.1	62.5 ± 0.1	62.5 ± 0.1
D— Diameter (Note 1)	12.5 ± 0.2	12.5 ± 0.2	12.5 ± 0.2	12.5 ± 0.2	12.5 ± 0.2
R— Radius of fillet, min	10	10	2	10	10
A— Length of reduced section	75, min	75, min	100, approximately	75, min	75, min
L— Overall length, approximate	145	155	140	140	255
B— Length of end section (Note 3)	35, approximately	25, approximately	20, approximately	15, approximately	75, min
C— Diameter of end section	20	20	20	22	20
E— Length of shoulder and fillet section, approximate	....	15	....	20	15
F— Diameter of shoulder	....	15	....	15	15

NOTE 1—The reduced section may have a gradual taper from the ends toward the center with the ends not more than 1 % large in diameter than the center.

NOTE 2—On Specimens 1 and 2, any standard thread is permissible that provides for proper alignment and aids in assuring tha the specimen will break within the reduced section.

NOTE 3—On Specimen 5 it is desirable, if possible, to make the length of the grip section great enough to allow the specimen t extend into the grips a distance equal to two thirds or more of the length of the grips.

FIG. 9 Various Types of Ends for Standard Round Tension Test Specimens

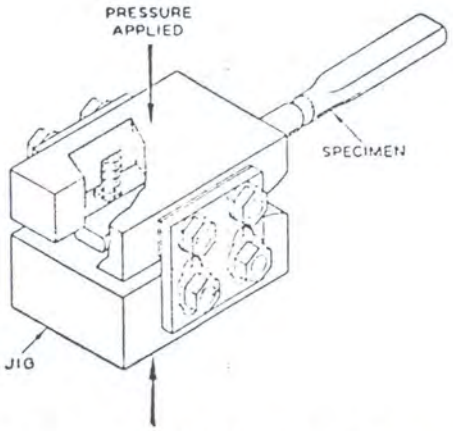
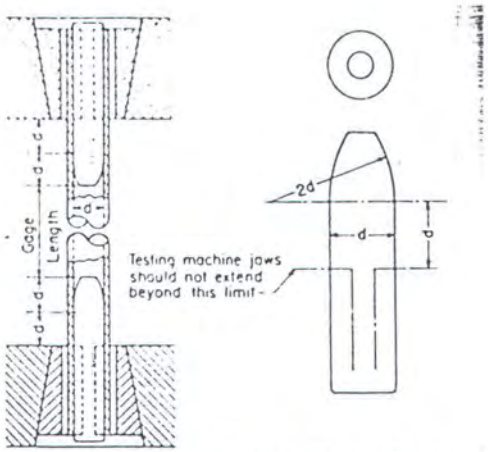
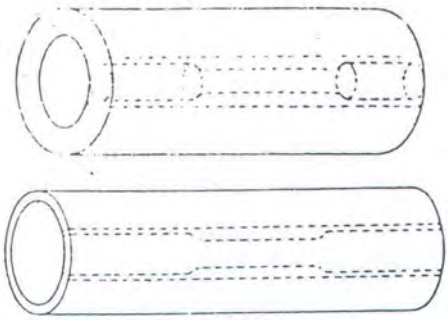


FIG. 10 Squeezing Jig for Flattening Ends of Full-Size Tension Test Specimens



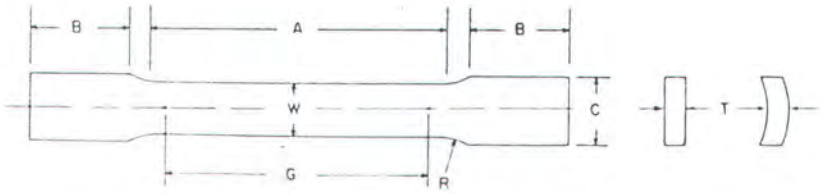
NOTE—The diameter of the plug shall have a slight taper from the line limiting the testing machine jaws to the curved section.

FIG. 11 Metal Plugs for Testing Tubular Specimens, Proper Location of Plugs in Specimen and of Specimen in Heads of Testing Machine



NOTE—The edges of the blank for the specimen shall be cut parallel to each other.

FIG. 12 Location from Which Longitudinal Tension Test Specimens Are to Be Cut from Large-Diameter Tube



Dimensions, mm

Nominal Width	Specimen 1	Specimen 2	Specimen 3
	12.5	40	40
G— Gage length	50.0 ± 0.1	50.0 ± 0.1	200.0 ± 0.2
W— Width (Note 1)	12.5 ± 0.2	40.0 ± 2.0	40.0 ± 2.0
T— Thickness	measured thickness of specimen		
R— Radius of fillet, min	12.5	25	25
A— Length of reduced section, min	60	60	230
B— Length of grip section, min (Note 2)	75	75	75
C— Width of grip section, approximate (Note 3)	20	50	50

NOTE 1—The ends of the reduced section shall not differ in width by more than 0.1 mm for Specimens 1, 2, and 3. There may be a gradual taper in width from the ends to the center, but the width at each end shall be not more than 1 % greater than the width at the center. A straight-sided 12.5-mm wide specimen may be used in place of the standard 12.5-mm wide specimen unless prohibited by product specifications.

NOTE 2—It is desirable, if possible, to make the length of the grip section great enough to allow the specimen to extend into the grips a distance equal to two thirds or more of the length of the grips.

NOTE 3—The ends of the specimen shall be symmetrical with the center line of the reduced section within 1.0 mm for Specimen 1 and 2.5 mm for Specimens 2 and 3.

NOTE 4—Specimens with sides parallel throughout their length are permitted, except for referee testing, provided: (*a*) the above tolerances are used; (*b*) an adequate number of marks are provided for determination of elongation; and (*c*) when yield strength is determined, a suitable extensometer is used. If the fracture occurs at a distance of less than $2W$ from the edge of the gripping device, the tensile properties determined may not be representative of the material. If the properties meet the minimum requirements specified, no further testing is required, but if they are less than the minimum requirements, discard the test and retest.

FIG. 13 Tension Test Specimens for Large-Diameter Tubular Products

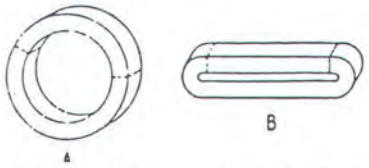
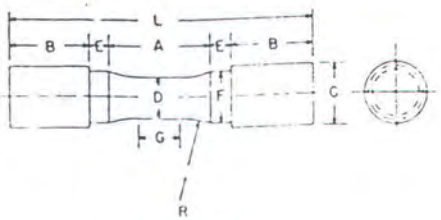


FIG. 14 Location of Transverse Tension Test Specimen in Ring Cut from Tubular Products

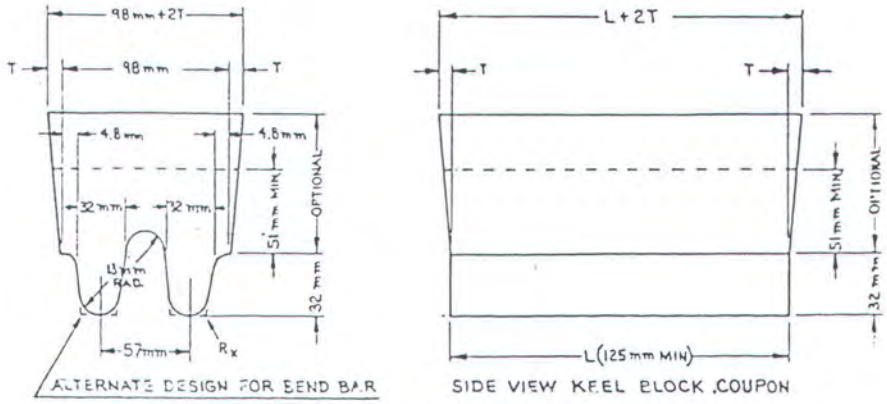


Dimensions, mm

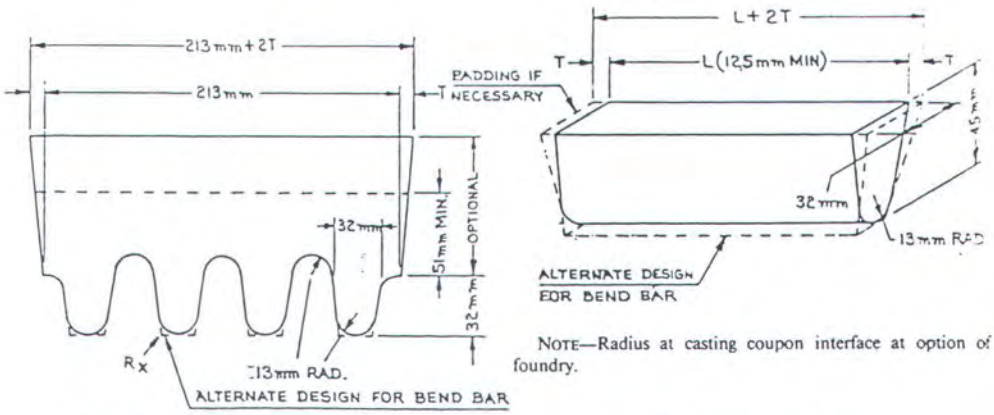
Nominal Diameter	Specimen 1	Specimen 2	Specimen 3
	12.5	20	30
G— Length of parallel	Shall be equal to or greater than diameter *D*		
D— Diameter	12.5 ± 0.2	20.0 ± 0.4	30.0 ± 0.6
R— Radius of fillet, min	25	25	50
A— Length of reduced section, min	32	38	60
L— Overall length, min	95	100	160
B— Length of end section, approximate	25	25	45
C— Diameter of end section, approximate	20	30	48
E— Length of shoulder, min	6	6	8
F— Diameter of shoulder	16.0 ± 0.4	24.0 ± 0.4	36.5 ± 0.4

NOTE—The reduced section and shoulders (dimensions *A*, *D*, *E*, *F*, *G*, and *R*) shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the load shall be axial. Commonly the ends are threaded and have the dimensions *B* and *C* given above.

FIG. 15 Standard Tension Test Specimen for Cast Iron



(*a*) Design for Double Keel Block Coupon

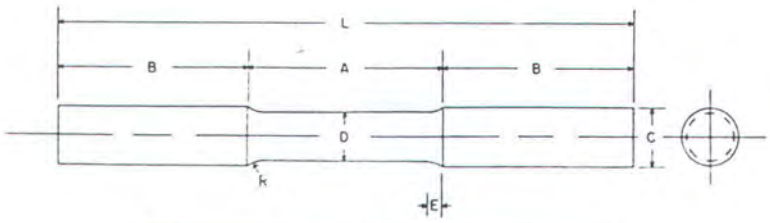


(*b*) Design for Multiple Keel Block Coupon (4 Legs)

NOTE—Radius at casting coupon interface at option of foundry.

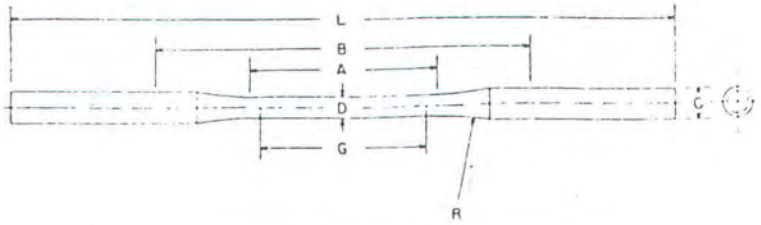
(*c*) Design for "Attached" Coupon

FIG. 16 Test Coupons for Castings (see Table 1 for Details of Design)



Dimensions, mm	
D—Diameter	16
R—Radius of fillet	8
A—Length of reduced section	64
L—Overall length	190
B—Length of end section	64
C—Diameter of end section	20
E—Length of fillet	5

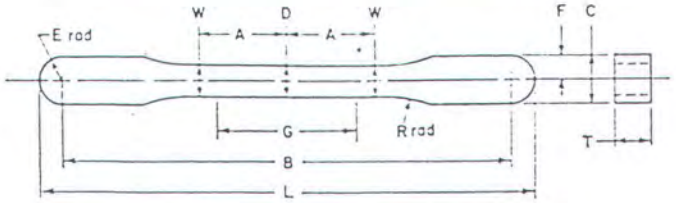
FIG. 17 Standard Tension Test Specimen for Malleable Iron



Dimensions, mm	
G—Gage length	50.0 ± 0.1
D—Diameter (see Note)	6.4 ± 0.1
R—Radius of fillet, min	75
A—Length of reduced section, min	60
L—Overall length, min	230
B—Distance between grips, min	115
C—Diameter of end section, approximate	10

NOTE—The reduced section may have a gradual taper from the ends toward the center, with the ends not more than 0.1 mm larger in diameter than the center.

FIG. 18 Standard Tension Test Specimen for Die Castings

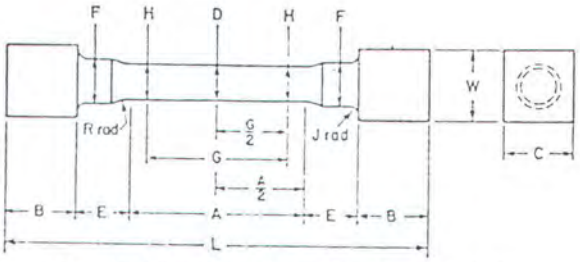


Approximate Pressing Area = 650 mm²

NOTE—Dimensions specified, except *G*, are those of the die.

Dimensions, mm	
G—Gage length	24.0 ± 0.1
D—Width at center	6.00 ± 0.03
W—Width at end of reduced section	6.25 ± 0.03
T—Compact to this thickness	5 to 6.5
R—Radius of fillet	25
A—Half-length of reduced section	16
B—Grip length	81
L—Overall length	90
C—Width of grip section	9.00 ± 0.03
F—Half width of grip section	4.50 ± 0.03
E—End radius	4.50 ± 0.03

FIG. 19 Standard Flat Unmachined Tension Test Specimen for Powdered Metal Products



Approximate Pressing Area of Unmachined Compact = 1000 mm²

Machining Recommendations

1. Rough machine to 9-mm diameter
2. Finish turn 6-mm diameter with radii and taper
3. Polish with 00 emery cloth
4. Lap with crocus cloth

Dimensions, mm	
G—Gage length	30.0 ± 0.1
D—Diameter at center of reduced section	6.0 ± 0.1
H—Diameter at ends of gage length	D + 0.02 to 0.05
R—Radius of fillet	6
A—Length of reduced section	32
L—Overall length (die cavity, length)	80
B—Length of end section	12
C—Compact to this end thickness	12.5 ± 1.0
W—Die cavity width	12.5
E—Length of shoulder and fillet	9
F—Diameter of shoulder	8
J—End fillet radius, max	2

NOTE—The gage length and fillets of the specimen shall be as shown. The ends as shown are designed to provide a total pressing area of approximately 600 mm². Other end designs are acceptable, and in some cases are required for high-strength sintered materials. Some suggested alternative end designs include:

1. Longer ends, of the same general shape and configuration as the standard, to provide more surface area for gripping.
2. Shallow transverse grooves, or ridges, may be pressed in the ends, to be gripped by jaws machined to fit the specimen contour.

FIG. 20 Standard Round Machined Tension Test Specimen for Powdered Metal Products

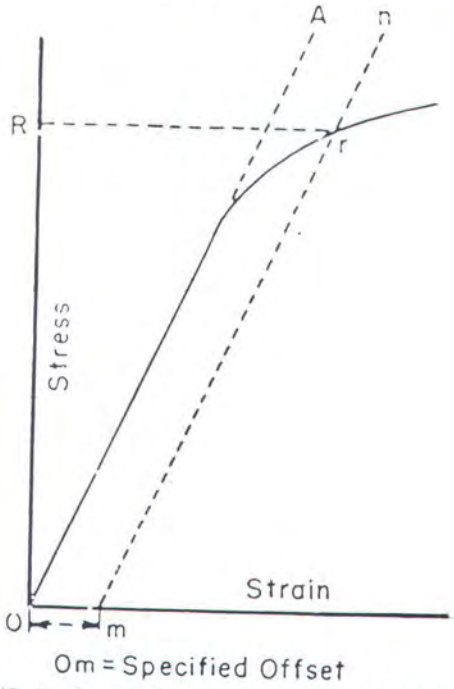


FIG. 21 Stress-Strain Diagram for Determination of Yield Strength by the Offset Method

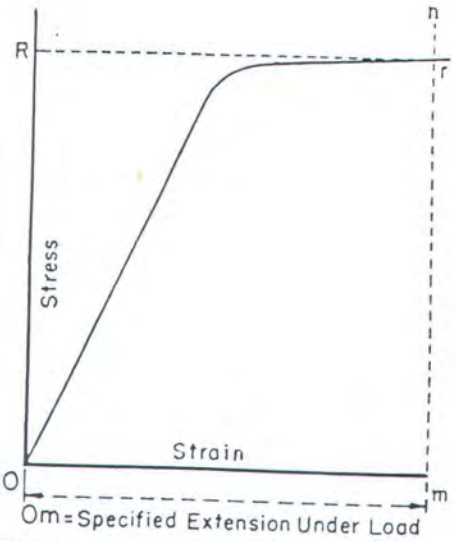


FIG. 22 Stress-Strain Diagram for Determination of Yield Strength or Yield Point by the Extension-Under-Load Method

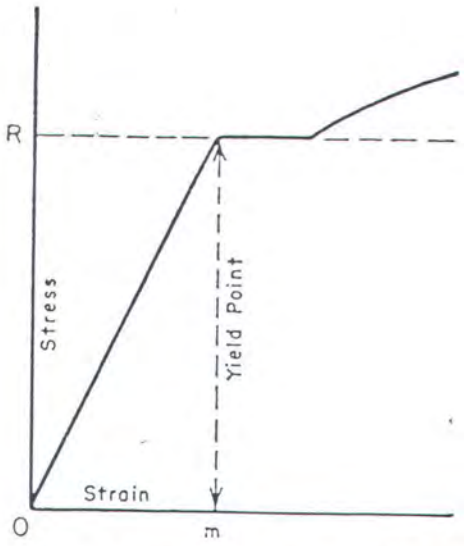


FIG. 23 Stress-Strain Diagram Showing Yield Point Corresponding with Top of Knee

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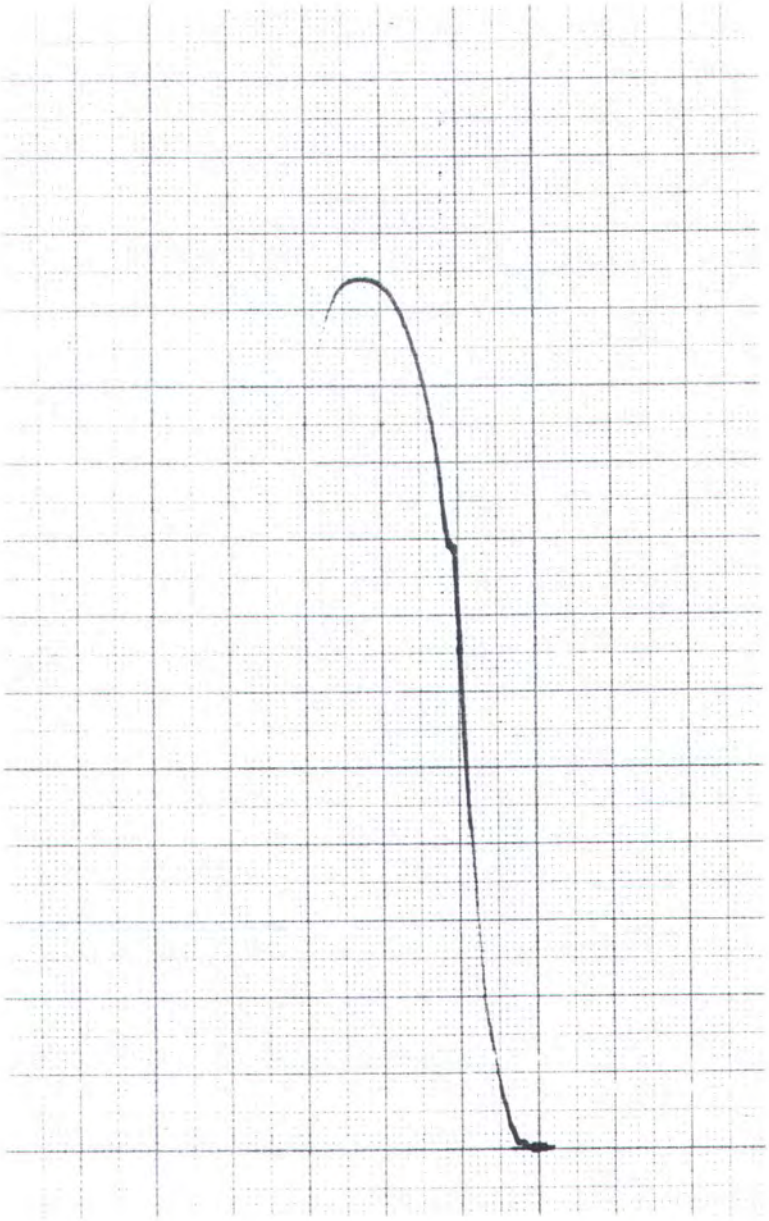
This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five year if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for addi standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting c responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you s make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

LAMPIRAN B

GRAFIK HASIL UJI TARIK



LAMPIRAN C

ASTM E 399-83

Standard Test Method for PLANE-STRAIN FRACTURE TOUGHNESS OF METALLIC MATERIALS[1]

This standard is issued under the fixed designation E 399; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This method has been approved for use by agencies of the Department of Defense and for listing in the DoD Index of Specifications and Standards

1. Scope

1.1 This test method covers the determination of the plane-strain fracture toughness (K_{Ic}) of metallic materials by tests using a variety of fatigue-cracked specimens having a thickness of 0.063 in. (1.6 mm) or greater.[2] The details of the various specimen and test configurations are shown in Annexes A1 through A7.

NOTE 1—Plane-strain fracture toughness tests of thinner materials that are sufficiently brittle (see 7.1) can be made with other types of specimens (**1**).[3] There is no standard test method for testing such thin materials.

1.2 This test method also covers the determination of the specimen strength ratio R_{xx} where x refers to the specific specimen configuration being tested. This strength ratio is a function of the maximum load the specimen can sustain, its initial dimensions and the yield strength of the material.

1.3 Measured values of plane-strain fracture toughness stated in inch-pound units are to be regarded as standard.

1.4 This test method is divided into two main parts. The first part gives general information concerning the recommendations and requirements for K_{Ic} testing. The second part is composed of annexes that give the displacement gage design, fatigue cracking procedures, and special requirements for the various specimen configurations covered by this method. In addition, an annex is provided for the specific procedures to be followed in rapid-load plane-strain fracture toughness tests. General information and requirements common to all specimen types are listed as follows:

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Practical Applications	4.2
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Plane-Strain Fracture Toughness	5.1.2
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Loading Fixtures	6.2
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Standard and Alternative Specimen Configurations	7.2
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Analysis of Test Record	9.1
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Validity Requirements on Specimen Size	9.1.3

[1] This test method is under the jurisdiction of ASTM Committee E-24 on Fracture Testing and is the direct responsibility of Subcommittee E24.01 on Fracture Mechanics Test Methods.

Current edition approved April 24, 1983. Published July 1983. Originally published as E 399 – 70 T. Last previous edition E 399 – 81.

[2] For additional information relating to the fracture toughness testing of aluminum alloys, see Method B 645.

[3] The boldface numbers in parentheses refer to the list of references at the end of this method.

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Fracture Appearance Descriptions	9.3
Reporting	10
Precision and Accuracy	11
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1.5 Special requirements for the various specimen configurations appear in the following order:

Bend Specimen $SE(B)$	Annex A3
Compact Specimen $C(T)$	Annex A4
Arc-Shaped Specimen $A(T)$	Annex A5
Disk-Shaped Compact Specimen $DC(T)$	Annex A6
Rapid Load $K_{Ic}(t)$ Tests	Annex A7

2. Applicable Documents

2.1 *ASTM Standards:*

B 645 Practice for Plane Strain Fracture Toughness Testing of Aluminum Alloys[4]

E 8 Methods of Tension Testing of Metallic Materials[5]

E 21 Recommended Practice for Elevated Temperature Tension Tests of Metallic Materials[6]

E 337 Test Method for Relative Humidity by Wet- and Dry-Bulb Psychrometer[7]

E 338 Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials[6]

E 616 Terminology Relating to Fracture Testing[6]

3. Summary of Test Method

3.1 This test method involves testing of notched specimens that have been precracked in fatigue by loading either in tension or three-point bending. Load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2 % apparent increment of crack extension is established by a specified deviation from the linear portion of the record. The K_{Ic} value is calculated from this load by equations that have been established on the basis of elastic stress analysis of specimens of the types described in this method. The validity of the determination of the K_{Ic} value by this test method depends upon the establishment of a *sharp-crack* condition at the tip of the fatigue crack, in a specimen of adequate size. To establish a suitable crack-tip condition, the stress intensity level at which the fatigue precracking of the specimen is conducted is limited to a relatively low value.

3.2 The specimen size required for testing purposes increases as the square of the ratio of toughness to yield strength of the material; therefore a range of proportional specimens is provided.

4. Significance and Use

4.1 The property K_{Ic} determined by this test method characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack under severe tensile constraint, such that the state of stress near the crack front approaches tritensile plane strain, and the crack-tip plastic region is small compared with the crack size and specimen dimensions in the constraint direction. A K_{Ic} value is believed to represent a lower limiting value of fracture toughness. This value may be used to estimate the relation between failure stress and defect size for a material in service wherein the conditions of high constraint described above would be expected. Background information concerning the basis for development of this test method in terms of linear elastic fracture mechanics may be found in Refs (1) and (2).

4.1.1 The K_{Ic} value of a given material is a function of testing speed and temperature. Furthermore, cyclic loads can cause crack extension at K_I values less than the K_{Ic} value. Crack extension under cyclic or sustained load will be increased by the presence of an aggressive environment. Therefore, application of K_{Ic} in the design of service components should be made with awareness to the difference that may exist between the laboratory tests and field conditions.

4.1.2 Plane-strain crack toughness testing is unusual in that there can be no advance assurance that a valid K_{Ic} will be determined in a particular test. Therefore it is essential that all of the criteria concerning validity of results be carefully considered as described herein.

4.1.3 Clearly it will not be possible to determine K_{Ic} if any dimension of the available stock of a material is insufficient to provide a specimen of the required size. In such a case the specimen strength ratio determined by this method will often have useful significance. However, this ratio, unlike K_{Ic}, is not a concept of linear elastic

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[4] *Annual Book of ASTM Standards*, Vol 02.02.

[5] *Annual Book of ASTM Standards*, Vols 02.02 and 03.01.

[6] *Annual Book of ASTM Standards*, Vol 03.01.

[7] *Annual Book of ASTM Standards*, Vols 07.01, 11.03, and 15.09.

fracture mechanics, but can be a useful comparative measure of the toughness of materials when the specimens are of the same form and size, and that size is insufficient to provide a valid K_{Ic} determination, but sufficient that the maximum load results from pronounced crack propagation rather than plastic instability.

4.1.3.1 The strength ratio for center-cracked plate specimens tested in uniaxial tension may be determined by Method E 338.

4.2 This method can serve the following purposes:

4.2.1 In research and development to establish, in quantitative terms, significant to service performance, the effects of metallurgical variables such as composition or heat treatment, or of fabricating operations such as welding or forming, on the fracture toughness of new or existing materials.

4.2.2 In service evaluation, to establish the suitability of a material for a specific application for which the stress conditions are prescribed and for which maximum flaw sizes can be established with confidence.

4.2.3 For specifications of acceptance and manufacturing quality control, but only when there is a sound basis for specification of minimum K_{Ic} values, and then only if the dimensions of the product are sufficient to provide specimens of the size required for valid K_{Ic} determination. The specification of K_{Ic} values in relation to a particular application should signify that a fracture control study has been conducted on the component in relation to the expected history of loading and environment, and in relation to the sensitivity and reliability of the crack detection procedures that are to be applied prior to service and subsequently during the anticipated life.

5. Definitions

5.1 Terminology E 616 is applicable to this method.

5.1.1 *stress-intensity factor*, K, K_1, K_2, K_3 [$FL^{-3/2}$]—the magnitude of the ideal-crack-tip stress field (a stress-field singularity) for a particular mode in a homogeneous, linear-elastic body.

NOTE—Values of K for mode 1, 2, and 3 are given by:

$$K_1 = \lim_{r \to 0} [\sigma_y (2\pi r)^{1/2}],$$

$$K_2 = \lim_{r \to 0} [\tau_{xy} (2\pi r)^{1/2}], \text{ and}$$

$$K_3 = \lim_{r \to 0} [\tau_{yz} (2\pi r)^{1/2}],$$

where r = a distance directly forward from the crack tip to a location where the significant stress is calculated.

Discussion—In this test method, mode I is assumed.

5.1.2 *plane-strain fracture toughness*—the crack-extension resistance under conditions of crack-tip plane strain.

NOTE 1—For example, in mode I for for slow rates of loading and negligible plastic-zone adjustment, plane-strain fracture toughness is the value of stress-intensity factor designated K_{Ic} [$FL^{-3/2}$] as measured using the operational procedure (and satisfying all of the validity requirements) specified in this test method, which provides for the measurement of crack-extension resistance at the start of crack extension and provides operational definitions of crack-tip sharpness, start of crack extension, and crack-tip plane strain.

NOTE 2—See also definitions of **crack-extension resistance, crack-tip plane strain, and mode.**

Discussion—In this test method, mode I is assumed.

5.1.3 *crack plane orientation*—an identification of the plane and direction of a fracture in relation to product geometry. This identification is designated by a hyphenated code with the first letter(s) representing the direction normal to the crack plane and the second letter(s) designating the expected direction of crack propagation.

5.1.3.1 The fracture toughness of a material usually depends on the orientation and direction of propagation of the crack in relation to the anisotropy of the material, which depends, in turn, on the principal directions of mechanical working or grain flow. The orientation of the crack plane should be identified wherever possible in accordance with the following systems **(11)**. In addition, the product form should be identified (for example, straight rolled plate, cross rolled plate, pancake forging, etc.).

5.1.3.2 For rectangular sections, the reference directions are identified as in Figs. 1 and 2, which give examples for a rolled plate. The same system would be useful for sheet, extrusions, and forgings with nonsymmetrical grain flow.

L = direction of principal deformation (maximum grain flow),

T = direction of least deformation, and

S = third orthogonal direction.

5.1.3.3 Using a two letter code, the first letter designates the *direction normal* to the crack plane, and the second letter the *expected direction of crack propagation*. For example, in Fig. 1 the T-L specimen has a fracture plane whose normal is in the width direction of a plate and an expected direction of crack propagation coincident with the direction of maximum grain flow or longitudinal direction of the plate.

5.1.3.4 For specimens that are tilted in respect to two of the reference axes, Fig. 2, the orientation is identified by a three-letter code. The code *L–TS*, for example, means that the crack plane is perpendicular to the direction of principal deformation (*L* direction), and the expected fracture direction is intermediate between *T* and *S*. The code *TS–L* means the crack plane is perpendicular to a direction intermediate between *T* and *S*, and the expected fracture direction is in the *L* direction.

5.1.3.5 For certain cylindrical sections where the direction of principal deformation is parallel to the longitudinal axis of the cylinder, the reference directions are identified as in Fig. 3, which gives examples for a drawn bar. The same system would be useful for extrusions or forged parts having circular cross section.

L = direction of maximum grain flow,
R = radial direction, and
C = circumferential or tangential direction.

6. Apparatus

6.1 *Loading*—Specimens should be loaded in a testing machine that has provision for autographic recording of the load applied to the specimen.

6.2 *Fixtures*—Fixtures suitable for loading the specimen configurations covered by this method are shown in the appropriate annex. These fixtures are so designed as to minimize the frictional contributions to the measured load.

6.3 *Displacement Gage*—The displacement gage output shall indicate the relative displacement of two precisely located gage positions spanning the crack starter notch mouth. Exact and positive positioning of the gage on the specimen is essential, yet the gage must be released without damage when the specimen breaks. A recommended design for a self-supporting, releasable gage is shown in Fig. 4 and described in Annex A1. The strain gage bridge arrangement is also shown in Fig. 4.

6.3.1 The specimen must be provided with a pair of accurately machined knife edges that support the gage arms and serve as the displacement reference points. These knife edges can be machined integral with the specimen as shown in Fig. 4 and Fig. 5 or they may be separate pieces fixed to the specimen. A suggested design for such attachable knife edges is shown in Fig. 6. This design is based on a knife edge spacing of 0.2 in. (5.1 mm). The effective gage length is established by the points of contact between the screw and the hole threads. For the design shown the major diameter of the screw has been used in setting this gage length. A No. 2 screw will permit the use of attachable knife edges for specimens having $W > 1$ in. (25 mm).

6.3.2 Each gage shall be checked for linearity using an extensometer calibrator or other suitable device; the resettability of the calibrator at each displacement interval should be within +0.000020 in. (0.00050 mm). Readings shall be taken at ten equally spaced intervals over the working range of the gage (see Annex A1). This calibration procedure should be performed three times, removing and reinstalling the gage in the calibration fixture between each run. The required linearity shall correspond to a maximum deviation of +0.0001 in. (0.0025 mm) of the individual displacement readings from a least-squares-best-fit straight line through the data. The absolute accuracy, as such, is not important in this application, since the method is concerned with relative changes in displacement rather than absolute values (see 9.1).

6.3.3 It is not the intent of this method to exclude the use of other types of gages or gage-fixing devices provided the gage used meets the requirements listed below and provided the gage length does not exceed those limits given in the annex appropriate to the specimen being tested.

7. Specimen Size, Configurations, and Preparation

7.1 *Specimen Size:*

7.1.1 In order for a result to be considered valid according to this method it is required that both the specimen thickness, B, and the crack length, a, exceed 2.5 $(K_{Ic}/\sigma_{YS})^2$, where σ_{YS} is the 0.2 % offset yield strength of the material for the temperature and loading rate of the test (**1, 5, 6**).

7.1.2 The initial selection of a size of specimen from which valid values of K_{Ic} will be obtained may be based on an estimated value of K_{Ic} for the material. It is recommended that the value of K_{Ic} be overestimated, so that a conservatively large specimen will be employed for the initial tests. After a valid K_{Ic} result is obtained with the conservative-size initial specimen, the specimen size may be reduced to an appropriate size [a and $B \geqq 2.5\ (K_{Ic}/\sigma_{YS})^2$] for subsequent testing.

7.1.3 Alternatively, the ratio of yield strength to Young's modulus can be used for selecting a

specimen size that will be adequate for all but the toughest materials:

σ_{YS}/E	Minimum Recommended Thickness and Crack Length	
	in.	mm
0.0050 to 0.0057	3	75
0.0057 to 0.0062	2½	63
0.0062 to 0.0065	2	50
0.0065 to 0.0068	1¾	44
0.0068 to 0.0071	1½	38
0.0071 to 0.0075	1¼	32
0.0075 to 0.0080	1	25
0.0080 to 0.0085	¾	20
0.0085 to 0.0100	½	12½
0.0100 or greater	¼	6½

When it has been established that 2.5 $(K_{Ic}/\sigma_{YS})^2$ is substantially less than the minimum recommended thickness given in the preceding table, then a correspondingly smaller specimen can be used. On the other hand, if the form of the available material is such that it is not possible to obtain a specimen with both crack length and thickness greater than 2.5 $(K_{Ic}/\sigma_{YS})^2$, then it is not possible to make a valid K_{Ic} measurement according to this method.

7.2 *Specimen Configurations*—The configurations of the various specimens are shown in the following annexes: Annex A3, Bend Specimen SE (B), Annex A4, Compact Specimen C (T), Annex A5, Arc-Shaped Specimen A (T), and Annex A6, Disk-Shaped Compact Specimen DC (T).

7.2.1 *Standard Specimens*—The crack length, a (crack starter notch plus fatigue crack) is nominally equal to the thickness, B, and is between 0.45 and 0.55 times the width, W. The ratio W/B is nominally equal to two.

7.2.2 *Alternative Specimens*—In certain cases it may be desirable to use specimens having W/B ratios other than two. Alternative proportions for bend specimens are $1 \leq W/B \leq 4$. For the other specimen configurations alternative specimens may have $2 \leq W/B \leq 4$. These alternative specimens shall have the same crack length-to-width ratio as the standard specimens. It should be appreciated that K_{Ic} values obtained using alternative specimen proportions may not agree with those obtained using the standard specimens (15).

7.3 *Specimen Preparation*—The dimensional tolerances and surface finishes shown on the specimen drawings given in Annexes A3 to A6 shall be followed in specimen preparation.

7.3.1 *Fatigue Crack Starter Notch*—Three forms of fatigue crack starter notches are shown in Fig. 7. To facilitate fatigue cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a V-notch should be 0.003 in. (0.08 mm) or less. If a chevron form of notch is used, the root radius may be 0.010 in. (0.25 mm) or less. In the case of a slot tipped with a hole it will be necessary to provide a sharp stress raiser at the end of the hole. Care should be taken to ensure that this stress raiser is so located that the crack plane orientation requirements (8.2.4) can be met.

7.3.2 *Fatigue Cracking*—Fatigue cracking shall be conducted in accordance with the procedures outlined in Annex A2. Fatigue cycling shall be continued until the fatigue crack will satisfy the requirements stated in the following two sections.

7.3.2.1 The crack length (total length of the crack starter configuration *plus* the fatigue crack) shall be between 0.45 and 0.55 W.

7.3.2.2 For a straight-through crack starter terminating in a V-notch (see Fig. 7), the length of the fatigue crack on each surface of the specimen shall not be less than 2.5 % of W or 0.050 in. (1.3 mm) min, and for a crack starter tipped with a drilled hole (see Fig. 7), the fatigue crack extension from the stress raiser tipping the hole shall not be less than 0.5 D or 0.050 in. on both surfaces of the specimen, where D is the diameter of the hole (1.3 mm) min. For a chevron notch crack starter (see Fig. 7), the fatigue crack shall emerge from the chevron on both surfaces of the specimen.

8. General Procedure

8.1 *Number of Tests*—It is recommended that at least three replicate tests be made for each material condition.

8.2 *Specimen Measurement*—Specimen dimensions shall conform to the tolerances shown in the appropriate annex. Three fundamental measurements are necessary for the calculation of K_{Ic}, namely, the thickness, B, the crack length, a, and the width, W.

8.2.1 Measure the thickness, B, to the nearest 0.001 in. (0.025 mm) or to 0.1 %, whichever is larger, at not less than three equally spaced positions along the line of intended crack extension from the fatigue crack tip to the unnotched side of the specimen. The average of these three meas-

urements should be recorded as B.

8.2.2 Measure the crack length, a, after fracture to the nearest 0.5 % at the following three positions: at the center of the crack front, and midway between the center of the crack front, and the end of the crack front on each surface of the specimen. Use the average of these three measurements as the crack length to calculate K_Q. The following requirements shall apply to the fatigue crack front: (*1*) The difference between any two of the three crack length measurements shall not exceed 10 % of the average. (*2*) For a chevron notch starter (see Fig. 7), the fatigue crack shall emerge from the chevron on both surfaces of the specimen, neither surface crack length shall differ from the average length by more than 10 %, and the difference between these two surface measurements shall not exceed 10 % of the average crack length. (*3*) For a straight-through starter notch (see Fig. 7) no part of the crack front shall be closer to the machined starter notch than 2.5 % W or 0.050 in. (1.3 mm) minimum, nor shall the surface crack length measurements differ from the average crack length by more than 15 %, and the differences between these two measurements shall not exceed 10 % of the average crack length.

8.2.3 Measure the width, W, as described in the annex appropriate to the specimen type being tested.

8.2.4 The plane of the crack shall be parallel to both the specimen width and thickness direction within ±10° (7).

8.3 *Loading Rate*—For conventional (static) testing load the specimen at a rate such that the rate of increase of stress intensity is within the range from 30 000 to 150 000 psi·in.$^{1/2}$/min (0.55 to 2.75 MPa·m$^{1/2}$/s). The loading rates corresponding to these stress intensity rates are given in the appropriate annex for the specimen being tested. For rapid-load testing the loading rates are given in Annex A7.

8.4 *Test Record*—Make a test record consisting of an autographic plot of the output of the load-sensing transducer versus the output of the displacement gage. The initial slope of the linear portion shall be between 0.7 and 1.5. It is conventional to plot the load along the vertical axis, as in an ordinary tension test record. Select a combination of load-sensing transducer and autographic recorder so that the load, P_Q, (see 9.1) can be determined from the test record with an accuracy of ±1 %. With any given equipment, the accuracy of readout will be greater than the larger the scale of the test record.

8.4.1 Continue the test until the specimen can sustain no further increase in load. In some cases the range of the chart will not be sufficient to include all of the test record up to maximum load, P_{max}. In any case, read the maximum load from the dial of the testing machine (or other accurate indicator) and record it on the chart.

9. Calculation and Interpretation of Results

9.1 *Interpretation of Test Record and Calculation of* K_{Ic}—In order to establish that a valid K_{Ic} has been determined, it is necessary first to calculate a conditional result, K_Q, which involves a construction on the test record, and then to determine whether this result is consistent with the size and yield strength of the specimen according to 7.1. The procedure is as follows:

9.1.1 Draw the secant line OP_5, shown in Fig. 7 through the origin of the test record with slope $(P/v)_5 = 0.95\ (P/v)_o$, where $(P/v)_o$ is the slope of the tangent OA to the initial linear part of the record (Note 6). The load P_Q is then defined as follows: if the load at every point on the record which precedes P_5 is lower than P_5 then P_5 is P_Q (Fig. 8 Type I); if, however, there is a maximum load preceding P_5 which exceeds it, then this maximum load is P_Q (Fig. 8 Types II and III).

NOTE 6—Slight nonlinearity often occurs at the very beginning of a record and should be ignored. However, it is important to establish the initial slope of the record with high precision and therefore it is advisable to minimize this nonlinearity by a preliminary loading and unloading with the maximum load not producing a stress intensity level exceeding that used in the final stage of fatigue cracking.

9.1.2 Calculate the ratio P_{max}/P_Q, where P_{max} is the maximum load the specimen was able to sustain (see 8.4). If this ratio does not exceed 1.10, proceed to calculate K_Q as described in the annex appropriate to the specimen being tested. If P_{max}/P_Q does exceed 1.10, then the test is not a valid K_{Ic} test because it is then possible that K_Q bears no relation to K_{Ic}. In this case proceed to calculate the specimen strength ratio.

9.1.3 Calculate 2.5 $(K_Q/\sigma_{YS})^2$ where σ_{YS} is the 0.2 % offset yield strength in tension (see Methods E 8). If this quantity is less than both the specimen thickness and the crack length, then K_Q is equal to K_{Ic}. Otherwise, the test is not a valid K_{Ic} test. Expressions for calculations of K_Q are given in the annex appropriate to the specimen being tested.

9.1.4 If the test result fails to meet the requirements in 9.1.2 or in 9.1.3, or both, it will be necessary to use a larger specimen to determine K_{Ic}. The dimensions of the larger specimen can be estimated on the basis of K_Q but generally will be at least 1.5 times those of the specimen that failed to yield a valid K_{Ic} value.

9.1.5 Calculate the specimen-strength ratio R_{xx} according to the annex appropriate to the specimen being tested.

9.2 *Fracture Appearance*—The appearance of the fracture is valuable supplementary information and shall be noted for each specimen. Common types of fracture appearance are shown in Fig. 9. For fractures of Types (a) or (b), measure the average width, f, of the central flat fracture area, and note and record the proportion of oblique fracture per unit thickness $(B\text{-}f)/B$. Make this measurement at a location midway between the crack tip and the unnotched edge of the specimen. Report fractures of Type (c) as full oblique fractures.

10. Report

10.1 The specimen configuration code as shown with the specimen drawing in the appropriate annex shall be reported. In addition, this code shall be followed with loading code (T for tension and B for bending) and the code for crack plane orientation (see Section 5). These latter two codes should appear in separate parentheses. For example, a test result obtained using the compact specimen (see Annex A4) might be designated as follows: C(T)(S-T). The first letter indicates compact specimen. The second letter indicates the loading was tension and the first of the last two letters indicate that the normal to the crack plane is in the direction of principal deformation and the second of these letters indicates the intended direction of crack propagation is in the direction of least deformation.

10.2 In addition, the following information should be reported for each specimen tested.

10.2.1 The form of the product tested, that is, forging, plate, casting etc.

10.2.2 Thickness, B.

10.2.3 Width (depth), W.

10.2.3.1 Offset of the loading holes, X, for the arc-shaped specimen.

10.2.3.2 Outer and inner radii, r_2 and r_1 for the arc-shaped specimen.

10.2.4 Fatigue precracking conditions in terms of:

10.2.4.1 Maximum stress intensity, K(max) and number of cycles for terminal fatigue crack extension over a length at least 2.5 % of the overall length of notch plus crack, and

10.2.4.2 The stress intensity range for terminal crack extension.

10.2.5 Crack length measurements.

10.2.5.1 At center of crack front,

10.2.5.2 Midway between the center and the end of the crack front on each side, and

10.2.5.3 At each surface,

10.2.6 Test temperature.

10.2.7 Relative humidity as determined by Method E 337.

10.2.8 Loading rate in terms of K_I (change in stress intensity factor per unit time) (2).

10.2.9 Load-displacement record and associated calculations.

10.2.10 Fracture appearance,

10.2.11 Yield strength (offset = 0.2 %) as determined by Methods E 8,

10.2.12 K_{Ic}, or K_Q followed by the parenthetical statement: "invalid according to section(s).....of ASTM Test Method E 399," and

10.2.13 R_{xx} where x refers to the specimen configuration as given in the appropriate annex.

10.2.14 P_{max}/P_Q.

10.3 It is desirable to list the information required in 10.1 and 10.2 in the form of a table. A suggested form for such a table is given in Fig. 10.

11. Precision and Bias

11.1 *Bias*—There is no accepted "standard" value for the plane strain fracture toughness of any material. In the absence of such a true value, any statement concerning bias is not meaningful.

11.2 *Precision*—The precision of a K_{Ic} determination is a function of the precision and bias of the various measurements of linear dimensions of the specimen and testing fixtures, the precision of the displacement measurement, and the bias of the load measurement as well as the bias of the recording devices used to produce the load displacement record and the precision of the constructions made on this record. It is not possible to make meaningful statements concerning precision and bias for all these measurements. However, it is possible to derive useful information concerning the precision of a K_{Ic} measurement in a global sense from three interlaboratory

test programs (17) (18). The results of these programs are summarized in Table 1 which gives the standard deviation of K_{Ic} for the bend specimen, the compact specimen, and the arc-shaped specimen as derived from tests on several high-strength alloys which were all very uniform in composition and structure. It should be appreciated that the measures of precision shown in Table 1 apply to tests on high-strength alloys that do not exhibit strong transitional behavior in terms of temperature or strain rate. If temperature and rate effects have a large influence on the toughness, increased scatter in K_{Ic} measurements may be noted. For example, within or below the transition range of a structural steel the initial advance of the fatigue crack will be controlled by abrupt fracture of local elements at the crack tip accompanied by rapid transfer of load to adjacent regions which then exhibit cleavage fracture. Under these circumstances, a statistical size effect may be noticed as the specimen size is changed, and tests on small specimens will be characterized by larger scatter than will tests on larger specimens.

TABLE 1 Grand Means and Standard Deviations for K_{Ic} as Obtained from Three Interlaboratory Test Programs[4]

	Bend Specimens			
	2219T851 σ_{YS} = 51.0 ksi (353 MPa)	4340 σ_{YS} = 238 ksi (1640 MPa)	18 Ni Marage σ_{YS} = 276 ksi (1902 MPa)	4340 σ_{YS} = 206 ksi (1419 MPa)
Grand mean $\bar{X}$, ksi·in.$^{1/2}$	32.7	44.2	51.8	79.8
Standard deviation, S	1.87	1.85	2.04	2.87
	Compact Specimens			
Grand mean $\bar{X}$, ksi·in.$^{1/2}$	32.4	45.5	53.9	79.4
Standard deviation, S	1.15	1.27	1.64	1.79

	Arc-Shaped Specimens (4335V, σ_{YS} = 192 ksi (1320 MPa))	
	$X/W = 0$	$X/W = 0.5$
Grand mean $\bar{X}$, ksi·in.$^{1/2}$	102.3	101.7
Standard deviation, S	3.50	2.36

[4] The standard deviation has been pooled for all laboratories testing a given alloy. Data for the bend and compact specimen can be found in Ref (17) and for the arc-shaped specimen in Ref (18).

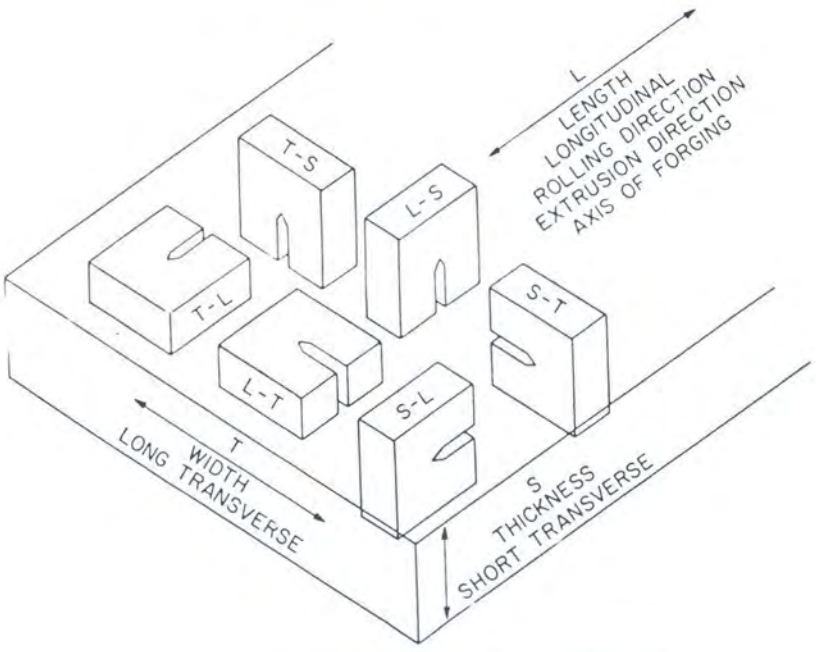


FIG. 1 Crack Plane Orientation Code for Rectangular Sections

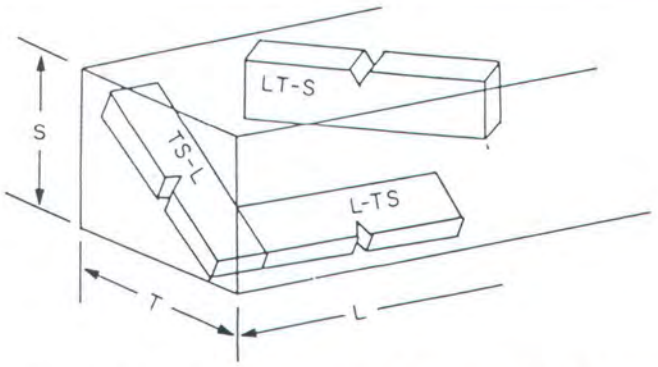


FIG. 2 Crack Plane Orientation Code for Rectangular Sections Where Specimens Are Tilted with Respect to the Reference Directions

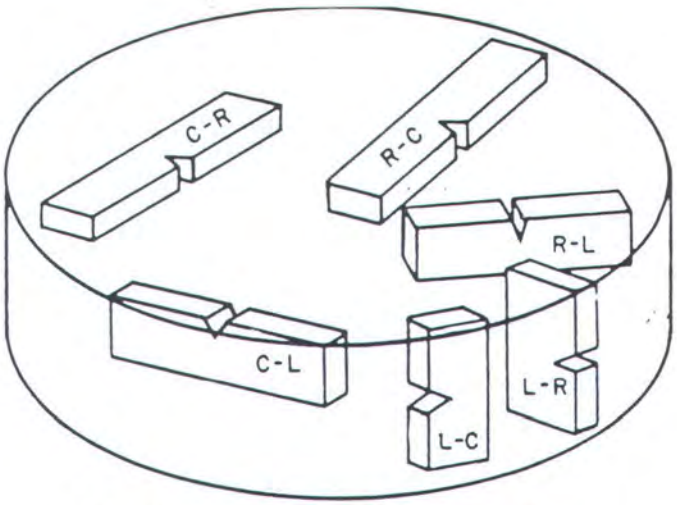


FIG. 3 Crack Plane Orientation Code for Bar and Hollow Cylinder

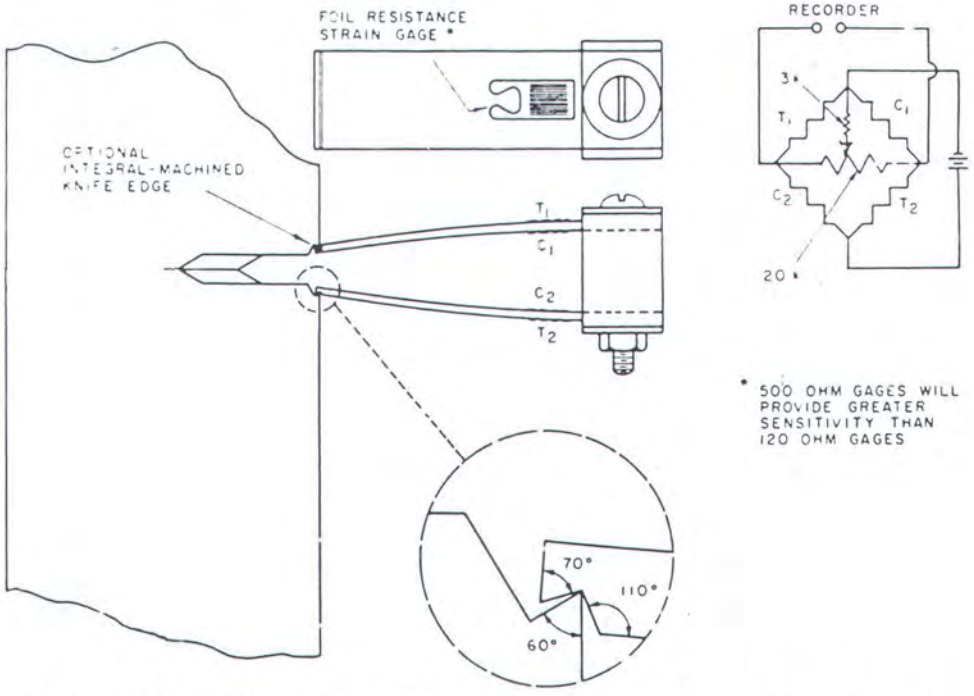
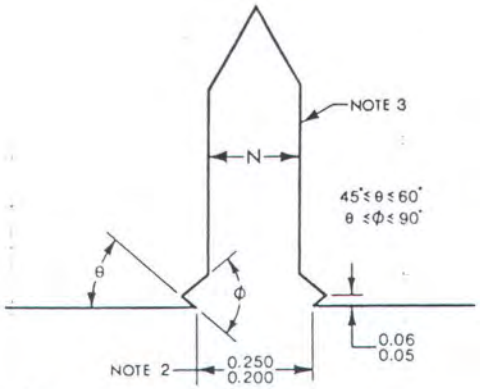


FIG. 4 Double-Cantilever Clip-In Displacement Gage Showing Mounting by Means of Integral Knife Edges (Gage Design Details are Given in Annex A1)



NOTE 1—Dimensions in inches.

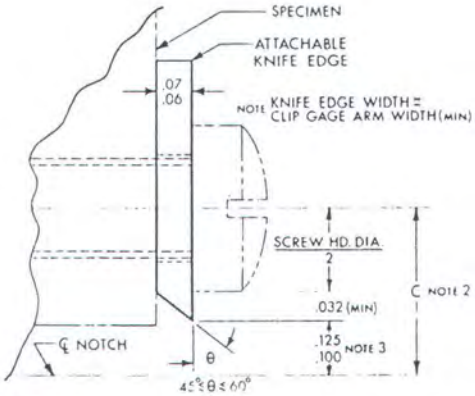
NOTE 2—Gage length shown corresponds to clip gage spacer block dimensions shown in Annex A1, but other gage lengths may be used provided they are appropriate to the specimen (see 6.3.3).

NOTE 3—For starter notch configurations see Fig. 7.

Metric Equivalents

in.	0.050	0.060	0.200	0.250
mm	1.3	1.5	5.1	6.4

Fig. 5 Example of Integral Knife Edge Design



NOTE 1—Dimensions are in inches.

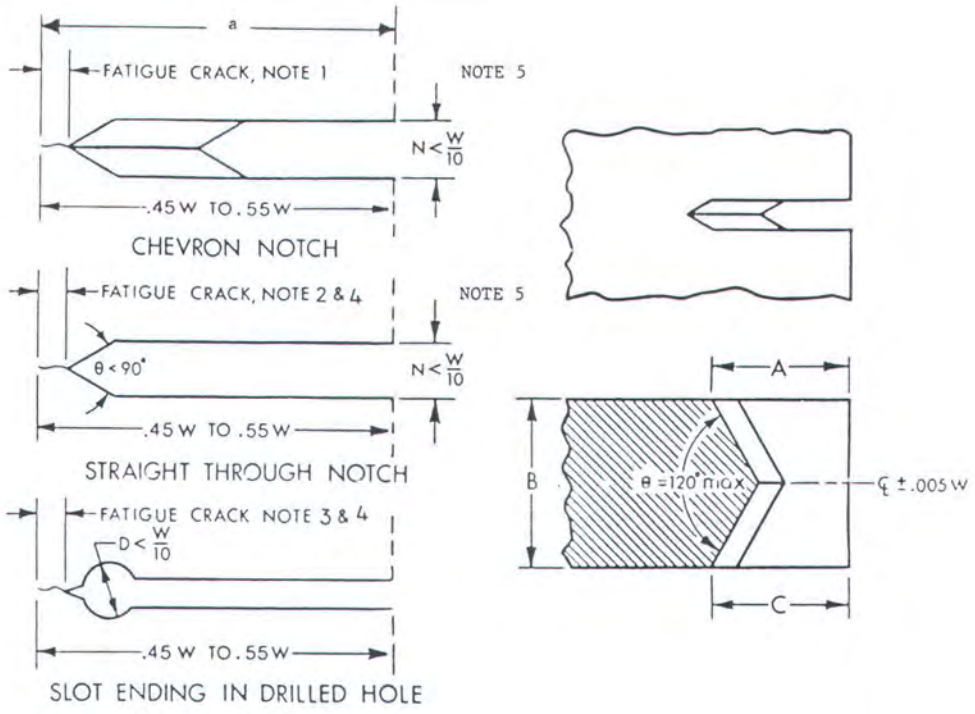
NOTE 2—Effective gage length = 2C + Screw Thread Diameter ≤ W/2. (This will always be greater than the gage length specified in A1.1.)

NOTE 3—Dimension shown corresponds to clip gage spacer block dimension in Annex A1.

Metric Equivalents

in.	0.032	0.06	0.07	0.100	0.125
mm	0.81	1.5	1.8	2.54	3.18

Fig. 6 Example of Attachable Knife Edge Design



(*a*) Starter Notches and Fatigue Cracks

NOTE 1—For a chevron crack starter notch the fatigue crack shall emerge on both surfaces of the specimen.

NOTE 2—Fatigue crack extension on each surface of the specimen containing a straight-through notch shall be at least 0.025 *W* or 0.050 in. (1.3 mm), whichever is larger.

NOTE 3—Fatigue crack extension on each surface of the specimen from the stress raiser tipping the hole shall be at least 0.5 *D* or 0.050 in. (1.3 mm), whichever is larger.

NOTE 4—Crack starter notch shall be perpendicular to the specimen surfaces and to the intended direction of crack propagation within ± 2°.

NOTE 5—Notch width *N* need not be less than 1/16 in. (1.6 mm).

(*b*) Detail of Chevron Notch

NOTE 1—A = C within 0.010 W

NOTE 2—Cutter tip angle 90° max

NOTE 3—Radius at chevron notch bottom 0.010 in. (0.25 mm) max

FIG. 7 Crack Starter Notch and Fatigue Crack Configurations

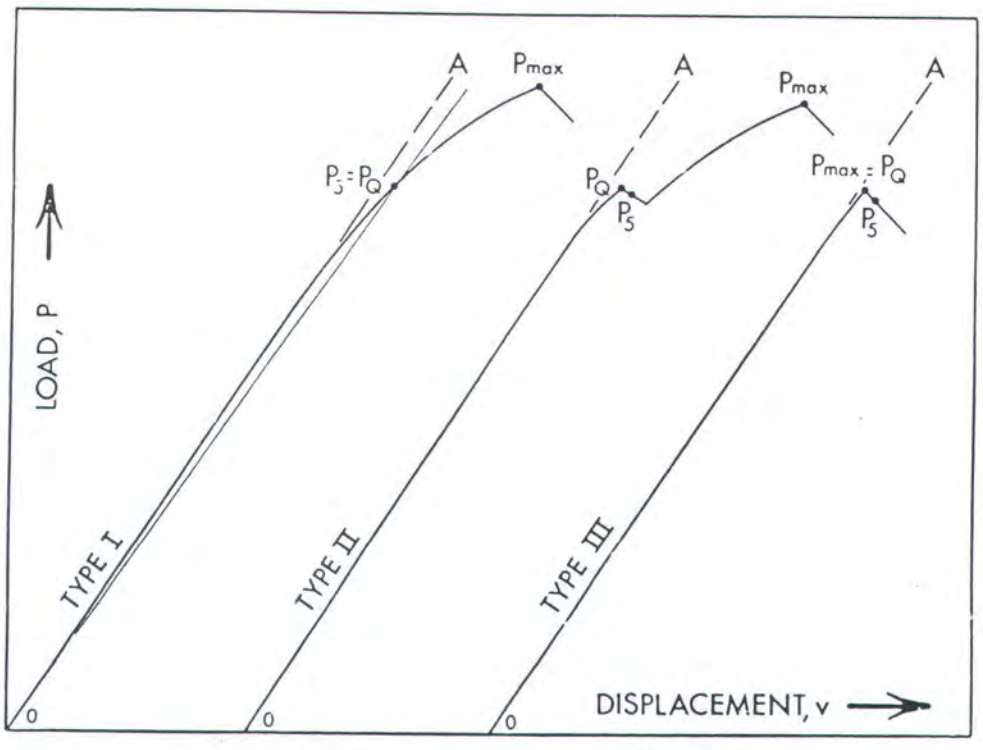


FIG. 8 Principal Types of Load-Displacement Records

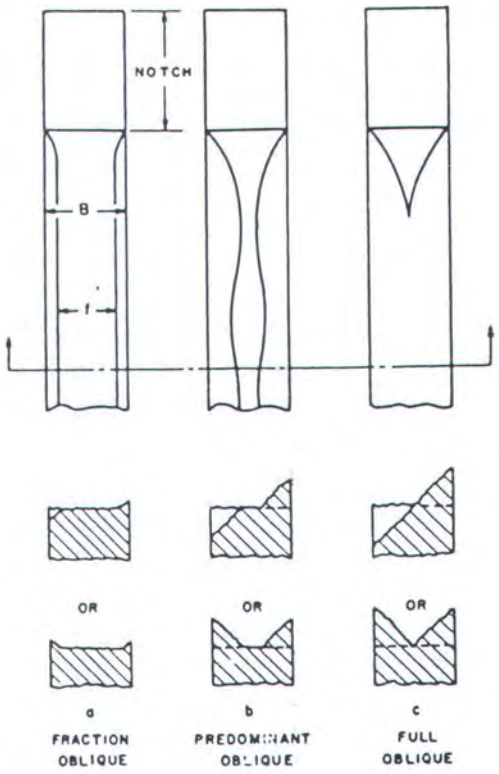


FIG. 9 Common Types of Fracture Appearance

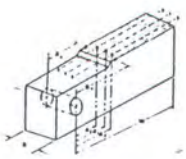
ASTM

K_{1c} DATA SHEET
(SAMPLE)

MATERIAL/FORM _____ HEAT TREAT _____

SPECIMEN I.D. _____ SPECIMEN TYPE _____

DATE ___/___/___ DATE REPORT



PARTICULARS	DATA	REF. PARAGRAPH
• Crack Plane Orientation		9.2
• Material 0.2% Offset Yield Strength, σ_{ys}, per E8		7.1.1
• Thickness, B		8.2.1
• Depth (Width), W		8.2.2
for - SE(B)		3.4.1 (Annex 3)
for - C(T)		4.4.1 (Annex 4)
for - DC(T)		6.4.1.2(Annex 6)
o Alt. Shaped Specimen -		
— Width, W		5.4.1 (Annex 5)
— Loading Hole Offset, X		5.4.1 (Annex 5)
— Outer and Inner Radii, r_1 & r_2		5.4.1 (Annex 5)

FATIGUE PRECRACKING	DATA	REF. PARAGRAPH
• $\frac{K_{max}}{E}$ <0.0021m$^{\frac{1}{2}}$ (0.00032m$^{\frac{1}{2}}$)		A2.3.3
• K_{max} <0.6 Kq		A2.3.3
• K_{max} ≤0.8 K_{1c}		A2.4.1 and A2.4.2
o If Temperature		
— $K_{max_{T1}}\left[\frac{\sigma_{ys}(T1)}{\sigma_{ys}(T2)}\right]$ ≤ Kq (T2)		A2.4.4
o Crack Length - Starter Slot plus Fatigue		
— a = 0.50W		A2.3.2 and Figure 4
— K_{max}, ΔK		
— Cycles for last 2.5% of "a"		

FRACTURE TEST	DATA	REF. PARAGRAPH
• Crack Lengths -		
— At Cente. of Crack Front (a_1)		8.2.2
— At Right of Center (a_2)		8.2.2
— At Left of Center (a_3)		8.2.2
— At Right of Surface (a_4)		8.2.2
— At Left Surface (a_5)		8.2.2
— Crack Plane Symmetry		8.2.4
— Loading Rate (ksi $\sqrt{in.}$/min.)		8.3
— Test Temperature		10.2.6
— Relative Humidity		10.2.7
— Load-Displacement Record		3.4 & 9.1

CALCULATION OF K & K_{ex}	DATA	REF. PARAGRAPH
• P_{max}/PQ < 1.1		9.1.2
— Kq SE(B)		3.5.3 (Annex 3)
— Kq C(T)		4.5.3 (Annex 4)
— Kq A(T)		5.5.3 (Annex 5)
— Kq DC(T)		6.5.3 (Annex 6)
• Valid K_{1c}		9.1.3
— K_{ex}		9.1.5

FIG. 10 Suggested Form of Table for Reporting Information Listed in 10.1 and 10.2

A4. SPECIAL REQUIREMENTS FOR THE TESTING OF COMPACT SPECIMENS

A4.1 Specimen

A4.1.1 The standard compact specimen is a single edge-notched and fatigue cracked plate loaded in tension. The general proportions of this specimen configuration are shown in Fig. A4.1.

A4.1.2 Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions.

A4.2 Specimen Preparation

A4.2.1 For generally applicable specifications concerning specimen size and preparation see Section 7.

A4.3 Apparatus

A4.3.1 *Tension Testing Clevis*—A loading clevis suitable for testing compact specimens is shown in Fig. A4.2. Both ends of the specimen are held in such a clevis and loaded through pins, in order to allow rotation of the specimen during testing. In order to provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces (4). Other clevis designs may be used if it can be demonstrated that they will accomplish the same result as the design shown.

A4.3.1.1 The critical tolerances and suggested proportions of the clevis and pins are given in Fig. A4.2. These proportions are based on specimens having $W/B = 2$ for $B > 0.5$ in. (12.7 mm) and $W/B = 4$ for $B \leq 0.5$ in. (12.7 mm). If a 280 000-psi (1930-MPa) yield strength maraging steel is used for the clevis and pins, adequate strength will be obtained for testing the specimen sizes and σ_{YS}/E ratios given in 7.1.3. If lower-strength grip material is used, or if substantially larger specimens are required at a given σ_{YS}/E ratio than those shown in 7.1.3, then heavier grips will be required. As indicated in Fig. A4.2 the clevis corners may be cut off sufficiently to accommodate seating of the clip gage in specimens less than 0.375 in. (9.5 mm) thick.

A4.3.1.2 Careful attention should be given to achieving as good alignment as possible through careful machining of all auxiliary gripping fixtures.

A4.3.2 *Displacement Gage*—For generally applicable details concerning the displacement gage see 6.3. For the compact specimen the displacements will be essentially independent of the gage length up to 1.2 W.

A4.4 Procedure

A4.4.1 *Measurement*—For a compact specimen measure the width, W, and the crack length, a, from the plane of the centerline of the loading holes (the notched edge is a convenient reference line but the distance from the centerline of the holes to the notched edge must be subtracted to determine W and a). Measure the width, W, to the nearest 0.001 in. (0.025 mm) or 0.1 %, whichever is larger, at not less than three positions near the notch location, and record the average value.

A4.4.1.1 For general requirements concerning specimen measurement see 8.2.

A4.4.2 *Compact Specimen Testing*—When assembling the loading train (clevises and their attachments to the tensile machine) care should be taken to minimize eccentricity of loading due to misalignments external to the clevises. To obtain satisfactory alignment keep the centerline of the upper and lower loading rods coincident within 0.03 in. (0.76 mm) during the test and center the specimen with respect to the clevis opening within 0.03 in. (0.76 mm).

A4.4.2.1 Load the compact specimen at such a rate that the rate of increase of stress intensity is within the range 30 to 150 ksi·in.$^{1/2}$/min (0.55 to 2.75 MPa·m$^{1/2}$/s) corresponding to a loading rate for a standard ($W/B = 2$) 1-in. thick specimen 4500 and 22 500 lbf/min (0.34 to 1.7 kN/s).

A4.4.2.2 For details concerning recording of the test record see 8.4.

A4.5 Calculations

A4.5.1 For general requirements and procedures in interpretation of the test record see 9.1.

A4.5.2 For a description of the validity requirements in terms of limitations on P_{max}/P_Q and the specimen size requirements see 9.1.2 through 9.1.3.

A4.5.3 *Calculation of K_Q*—For the compact specimen calculate K_Q in units of ksi·in.$^{1/2}$ (MPa·m$^{1/2}$) from the following expression (Note A4.1)

$$K_Q = (P_Q/BW^{1/2}) \cdot f(a/W)$$

where:

$$f(a/W) = \frac{(2 + a/W)(0.886 + 4.64a/W - 13.32a^2/W^2 + 14.72a^3/W^3 - 5.6a^4/W^4)}{(1 - a/W)^{3/2}}$$

where:

P_Q = load as determined in 9.1.1, klbf (kN),
B = specimen thickness as determined in 8.2.1, in. (cm),
W = specimen width, as determined in A4.4.1, in. (cm), and
a = crack length as determined in 8.2.2 and A4.4.1, in. (cm).

To facilitate calculation of K_Q, values of $f(a/W)$ are tabulated below for specific values of a/W.

Compact Specimens

a/W	$f(a/W)$	a/W	$f(a/W)$
0.450	8.34	0.500	9.66
0.455	8.46	0.505	9.81
0.460	8.58	0.510	9.96
0.465	8.70	0.515	10.12
0.470	8.83	0.520	10.29
0.475	8.96	0.525	10.45
0.480	9.09	0.530	10.63
0.485	9.23	0.535	10.80
0.490	9.37	0.540	10.98
0.495	9.51	0.545	11.17
		0.550	11.36

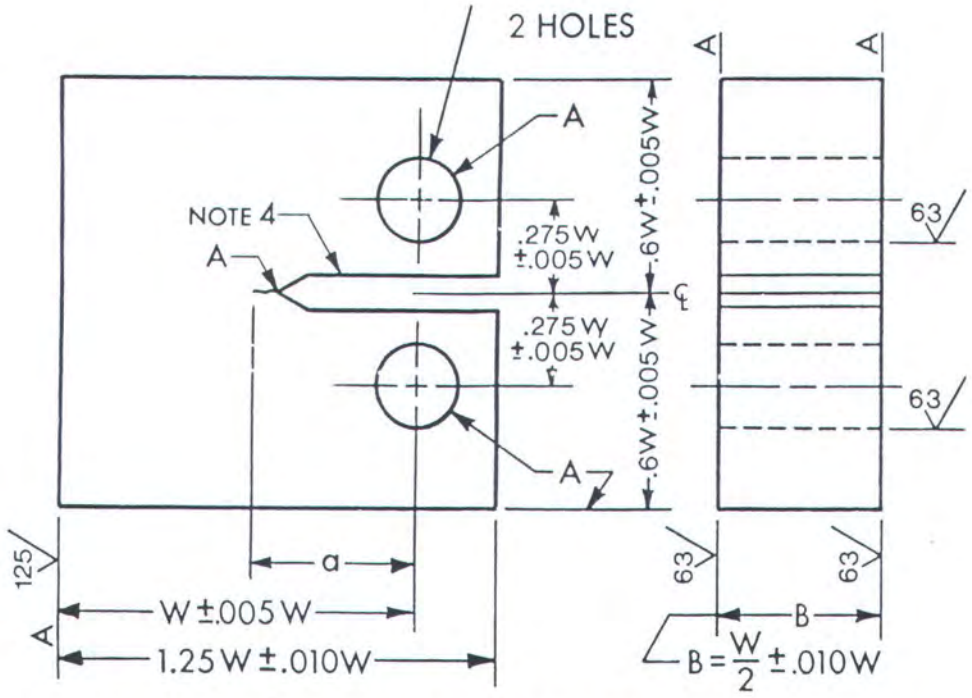
NOTE A4.1—The expression in A4.5.3 is considered to be accurate within ±0.5 % over the range of a/W from 0.2 to 1 **(12) (13)**.

4.5.4 *Calculation of R_K*—For the compact specimen calculate the specimen strength ratio (which is dimensionless and has the same value in any consistent system of units):

$$R_K = \frac{2P_{max}(2W + a)}{B(W - a)^2\sigma_{YS}}$$

where:

P_{max} = maximum load that the specimen was able to sustain,
B = thickness of specimen as determined in 8.2.1,
W = width of the specimen as determined in A4.4.1,
a = crack length as determined in 8.2 2 and A4.4.1, and
σ_{YS} = yield strength in tension (offset = 0.2 %) (see Methods E 8).



NOTE 1—*A* surfaces shall be perpendicular and parallel as applicable to within 0.002 *W* TIR.

NOTE 2—The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen within 0.005 *W*.

NOTE 3—Integral or attachable knife edges for clip gage attachment to the crack mouth may be used (see Fig. 5 and 6).

NOTE 4—For starter notch and fatigue crack configuration see Fig. 7.

FIG. A4.1 Compact Specimen C (T) Standard Proportions and Tolerances