DETERMINATION OF FRACTURE TOUGHNESS OF TOOL STEELS

A. K. Sheikh[1], A.F.M. Arif[1], S.Z. Qamar[1]

1:Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia, anwarks@kfupm.edu.sa

ABSTRACT

Metalworking dies are made of high strength tool steels. These dies are subjected to repeated thermo-mechanical loading cycles. Fatigue, wear, and plastic deformation are the three major modes of in-service die failure, fatigue fracture being the most dominant one. Plane-strain fracture toughness (K_{IC}) is the most important material property in the prediction and prevention of fracture, and in damage tolerance assessment. As fracture is the principal die failure mode, determination of K_{IC} becomes critical to evaluating and predicting die performance. Traditional methods of determining K_{IC} are not always practical due to special manufacturing requirements in preparing standard test specimens with sufficient degree of precision, especially for high strength tool steels. Even if such specimens are available, testing for K_{IC} at high temperatures becomes difficult. Attempts have been made in literature to correlate K_{IC} of some steels with fundamental mechanical properties such as yield strength (σ_Y) and Charpy impact energy (CVN). It is known with certainty that the yield strength of steels is quite sensitive to temperature and strain-rate changes. Therefore, it seems possible to use the correlations between impact energy, yield strength and fracture toughness as components of a predictive model for determination of K_{IC} at ambient as well as elevated temperatures. This paper reviews the published data on impact energy and fracture toughness of a variety of steels including some high strength steels as well as tool steels. A strategy is then proposed to use empirical relationships between fracture toughness and Charpy impact energy to assess K_{IC} of ultrahigh strength steels (such as H-13) at different tempering and specimen temperatures.

Keywords: *toughness, K_{IC}, impact energy, CVN, Charpy test, tool, steels, strength, metalworking, correlation, tempering temperatures, temperatures*

الملخص

تتعرض قوالب تشكيل المعادن المصنوعة من الفولاذ عالي القوة إلى دورات متكررة من التحميل الميكانيكي والحراري مما يسبب إخفاقها بسبب الكلال أو التآكل أو التشوه اللادائني. ويعتبر الكسر بسبب الكلال أهم مسببات إخفاق القوالب.

وقد وجد أن المتانة ضد الكسر مستوى الانفعال أهم خواص المادة عند تقدير القابلية للكسور والوقاية منها . ولهذا يتطلب تقويم أداء قوالب التشكيل ودرجة تحملها للظروف التشغيلية إيجاد متانة الكسر مستوى الانفعال. وقد صفت الطرق التقليدية لإيجاد متانة الكسر مستوي الانفعال بأنها غير عملية لأنها تحتاج إلى تصنيع عينات غاية في الدقة وخاصة في حالة الفولاذ عالي القوة، كما تسبب التقويم عند درجات الحرارة العالية مصاعب إضافية في حالة استخدام الطرق التقليدية. وقد حاول الباحثون الربط بين متانة الكسر مستوي الانفعال والخواص الميكانيكية الأساسية مثل مقاومة الخضوع وطاقة صدم

شاربي(وتم الوصول إلى حقيقة أن مقاومة الخضوع تتأثر كثيراً بدرجة التغيرات في الحرارة ومعدل الانفعال.ولهذا يتضح إمكانية استخدام العلاقة بين طاقة الصدم ومقاومة الخضوع والمتانة ضد الكسر كعناصر أساسية لنموذج يستخدم للتنبؤ بقيم متانة الكسر مستوي الانفعال عند درجات الحرارة الدنيا والعليا.

ويتسعرض هذا البحث البيانات المنشورة عن طاقة الصدم ضد الكسر لعدة أنواع من الفولاذ مع التركيز علـى الفـولاذ عالي القوة والفولاذ المستخدم في إنتاج العدد والقوالب. ويقدم البحث استراتيجية لاستخدام علاقات تجريبية بين طاقـة الصدم والمتانة ضد الكسر لإيجاد قيم المتانة ضد الكسر مستوي الانفعال (K_IC) للفولاذ فائق القوة مثل (H-13) وذلك عند درجات مختلفة من حرارة التطبيع وحرارة التشغيل.

1. INTRODUCTION

Dies and tools used in hot metal forming (extrusion, forging, rolling, etc) are exposed to high pressures/forces, elevated temperatures, mechanical and thermal fatigue. The three main modes of in-service die failure are fatigue (brittle failure through crack propagation), wear (gradual wearing out of the bearing surface), and deflection (plastic deformation). Out of these three, fatigue fracture is the principal cause of failure. Brittle failures are generally located at a section change, sharp corner, stamp mark, etc. Large cyclic stresses, combined with regions of high stress concentration in cavities, lead to crack growth. The high-strength hardened material generally results in a brittle failure. Reliable determination of fracture toughness of the die material is thus critically important. However, as die steels have a combination of high-hardness and high-strength, and are used at elevated temperatures, standard plane-strain fracture toughness (K_{IC}) testing methods become impracticable. Alternate testing procedures, together with empirical/semi-empirical correlations of K_{IC} to other data, are then more viable and economical.

1.1 Fracture Toughness Testing

ASTM Standard E399-90 (revised 1997) prescribes the “standard test method for plane-strain fracture toughness of metallic materials.” The crack-tip plastic region is small compared to crack length and to specimen dimension in the constraint direction. From a record of load versus crack opening and from previously determined relations of crack configuration to stress-intensity, plane-strain fracture toughness can be measured accurately provided all the criteria for a valid test are met.

For tougher, more ductile steels, specimens large enough to ensure loading under plane-strain conditions are often larger than the structures to be built. Consequently, other toughness tests and procedures are used. For many steels of technical interest (tool and die steels in particular), Charpy-type specimens can be used effectively with the root of the V-notch extended by fatigue cracking. Moreover, testing of precracked Charpy specimens can yield values that are strongly related to K_{IC} values.

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1.2 Current Work

This paper is based on the literature review for an ongoing study on the development of a die life enhancement strategy for hot extrusion of aluminum alloys. The basic premise is that the life of a hot working die is a trade-off between hardness and toughness. Material properties of tool steels (especially H-13) will be investigated, after heat treatment at different tempering temperatures and times, and at different working temperatures. The study encompasses empirical data (both from locally performed experiments, and from reported literature) from Charpy impact tests, axial loading fatigue tests, surface hardness measurements, and electron microscopy.

As an initial part of the above-mentioned study, the current paper focuses on an in-depth review of Charpy impact testing and fracture toughness testing of tool steels, variation of *CVN* and K_{IC} with temperature, transition temperature behavior of *CVN* and K_{IC}, empirical correlations between *CVN* and K_{IC} and between impact and toughness transition-temperatures. The objective of this literature survey is to enunciate a strategy for prediction of K_{IC} for high strength tool and die steels from fundamental mechanical properties.

2. THE TRANSITION TEMPERATURE APPROACH

Laboratory test specimens and methods cannot duplicate the actual dimensions and conditions of real structural components. To compensate for the worst possible fracture conditions in the field, experimental conditions were employed in earlier fracture toughness testing that would inhibit material capacity to deform plastically. This was achieved mainly by elevating the yield strength through a combination of low test-temperatures, high strain-rates, and a multiaxial stress state caused by the presence of a notch or defect in the sample.

The impact property of a material is its resistance to fracture when a sudden and dynamic load is applied. The *Charpy V-notch impact test* procedure, covered by ASTM Standard E 23-01 (revised 2001), offers quite a severe test of material toughness. The sample is a simple notched beam that is impacted in three-point bending. Very high strain rates are employed to load a notched specimen, as the specimen absorbs the impact of a falling pendulum. Also, the test is carried out over a range of temperatures. The maximum height to which the pendulum rises after fracturing the sample can be used to measure the amount of energy absorbed by the notched bar.

Some typical curves for impact energy versus test temperatures for different metals are plotted in Fig-1 [Hertzberg, 1999]. For a wide range of temperatures, most structural steels exhibit an upper-plateau and a lower-plateau for absorbed energy. These are commonly called the *upper-shelf* energy and the *lower-shelf* energy, respectively. The transition from upper shelf to lower shelf for most low-strength structural steels occurs abruptly within a very narrow range of temperatures. Higher-strength steels (quenched and tempered) exhibit a more gradual

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transition. At the *transition temperature* (where the abrupt drop in absorbed energy is observed), the specimen also exhibits a change from ductile to brittle behavior. The transition is thus also referred to as the *ductile to brittle transition temperature* (DBTT).

Defining the *transition temperature* in the case of a discontinuous or abrupt change in the fracture energy curve would be simple. For smooth curves however, it can be defined either as a specific energy level (13.5 or 20 or 27 J) or at some fraction of the maximum or shelf energy. Unfortunately, transition temperature criterion based on a prescribed energy level varies with material. [Gross, 1970] suggests (for various steels in the 415-965 MPa strength range) that the energy level for the transition temperature criterion should increase with increasing strength.

3. LIMITATIONS OF THE TRANSITION TEMPERATURE APPROACH

Though providing a simple and easy qualitative test of fracture toughness for a wide range of engineering materials, a notable limitation of the transition temperature methodology is that the transition temperature varies with specimen thickness. This happens due to the stress-state shift from plane-stress to plane-strain. [McNicol, 1965] determined that for several steels, the transition temperature increased with increasing Charpy bar thickness. It should be expected that the transition temperature would reach a limiting value when full plane-strain condition is reached.

It can thus be concluded that laboratory results may not have any bearing on transition temperature characteristics of the actual component if the sample thickness is different from the component thickness. Many metals and alloys, especially at lower strength levels are too tough and too ductile to fracture under plane-strain conditions in the sizes normally used in structures. The **dynamic tear test** (DT) and the **drop-weight tear test** (DWTT) were developed to defeat this problem. As outlined in Fig-2, both these tests involve three-point bending of a notched bar. The **DT** procedure has been standardized under ASTM Standard E604-83 (revised 1994), while **DWTT** is covered by ASTM Standard E436-91 (revised 1997). Samples are fractured using either the pendulum or drop-weight machines, and the fracture energy measured from a calibrated scale. DWTT and DT can thus be thought of as oversized Charpy samples. Specimens being much thicker and wider than the Charpy specimen, there is a much greater plastic constraint at the notch root. Transition temperature is thus shifted to significantly higher temperatures.

4. IMPACT ENERGY AND K_{IC} CORRELATIONS

Several investigators [Marandet and Sanz, 1977], [Rolfe and Novak, 1970], [Sailors and Corten, 1973], [Begley and Logsdon, 1971], [Barsom and Rolfe, 1970] have made an attempt to develop empirical correlations between Charpy energy and fracture toughness parameters such as K_{IC}. There are some notable differences between the Charpy test and typical fracture mechanics tests. Charpy specimen contains a blunt notch while fracture mechanics samples have sharp fatigue cracks; Charpy specimen is subsize in comparison with standard K_{IC} dimensions; Charpy tests are based on impact loading while most fracture toughness tests replicate quasistatic conditions. Still, the Charpy test has multiple advantages: sample is easy to prepare, test method is simple and quick, cost of test machinery is low, and cost per test is also small.

However, since dynamic Charpy data are being compared with static fracture toughness values, this test method should be considered valid only for materials that exhibit little or no strain-rate sensitivity. [Orner and Hartbower, 1961] suggested that by conducting the test under both impact and slow-bending conditions, a precracked Charpy sample could be utilized to determine the strain-rate sensitivity of a given material. [Barsom and Rolfe, 1971] later confirmed this proposition through comparison of static and dynamic test results obtained from precracked Charpy V-notch (*CVN*) and plane-strain fracture toughness samples for various steels in the 275-1725 MPa strength range. Transition temperature shift, as shown in Fig-3, was the most noticeable for low-strength steels.

Static (K_{IC}) and dynamic (K_{ID}) plane-strain fracture toughness values are plotted against test temperature in Fig-4. It should be noted that there was a gradual increase in K_{IC} with temperature for high-strength steels, but a dramatic shift to higher values for low-strength and medium-strength alloys. Also, a correlation between K_{IC} and plane-strain ductility transitions was observed and reinforced by the fact that both transitions have a relationship to fracture mechanism shift from cleavage at low temperatures to microviod coalescence at high temperatures [Barsom and Pellegrino 1973] and [Lange and Loss 1970]. A general conclusion from Fig-4 is that fracture toughness increases with temperature for both strain-rate sensitive and insensitive materials. It is notable that the predicted K_{IC} values (dashed line), obtained by applying the appropriate temperature shift from Fig-3 to the dynamic K_{IC} data (continuous line), were validated by experiments. *Dynamic K_{IC} testing is quite complex and thus not possible for many laboratories. K_{ID} estimation from more easily determined K_{IC} values thus presents great potential for evaluation of fracture properties related to strain-rate induced temperature shift.*

[Barsom and Rolfe, 1970] attempted an empirical correlation between K_{IC} and *CVN* values; Fig-5. These relations (and those proposed by various other researchers) are functions of material type, test temperature range, notch sharpness, and strain rate. They also depend upon notch initiation: precracked *CVN* sample as against impact testing at slow strain rates. [Roberts and Newton, 1981] examined 15 such correlations and concluded that no single correlation covers all possible test conditions and material types. Moreover, due to the inherent scatter of K_{IC} and *CVN* measurements, results from these correlations also exhibit a rather wide scatter band.

Some other important points should also be kept in mind. Existence of a *CVN*- K_{IC} correlation would appear to imply that we can directly compare data from static and dynamic fracture tests. This is acceptable for high-strength materials (σ_y > 825 MPa), as the ones in Fig-5, where strain-rate effects are minimal. However, for strain-rate sensitive materials, a two-step strategy is advisable. K_{ID} values should be first deduced from impact *CVN* data using an appropriate correlation, and then K_{IC} values should be estimated employing the relevant temperature shift factor.

5. PROPOSED STRATEGY

5.1 Cold Work Tool Steels

Transition in K_{IC} or *CVN* values for steels usually takes place below room temperatures. For tool steels used in cold working or in sub-zero atmospheres, a K_{IC} prediction strategy based on the transition temperature approach could thus be quite suitable. [Marandet and Sanz, 1977] employed a multi-step approach to predict a K_{IC}-temperature curve for a set of medium-strength steels having various heat treatments. By taking K_{IC} transition-temperature (TK^*_{IC}) as the temperature at which toughness increases rapidly, and noting that for most steels this rapid escalation takes place in the 60-100 MPa√m toughness range, they defined TK^*_{IC} as the temperature for which K^*_{IC} = 100 MPa√m. Similarly, they defined $TK28$ as the impact transition temperature, the temperature at which Charpy V-Notch energy is *CVN* = 28 J. By observing the transition trends for the steels studied, they suggested the relationship

$$TK^*_{IC} = 9 + 1.37\,TK28 \qquad (^\circ C) \qquad \text{(a)}$$

They also determined that by shifting the actual K_{IC}-temperature curves until TK^*_{IC} coincided with $TK28$, a K_{IC}-*CVN* correlation can be established as

$$K_{IC} = 19\,(CVN)^{1/2} \qquad (\text{MPa}\sqrt{\text{m}}, \text{J}). \qquad \text{(b)}$$

The multi-step K_{IC} prediction scheme then consists of (i) determining impact transition curve, (ii) obtaining K_{IC} values from *CVN* values at different temperatures by using (b), plotting K_{IC}-temperature curve, (iii) finding TK^*_{IC} from $TK28$ using (a), and (iv) shifting the obtained K_{IC}-temperature curve so that it passes through the point ($T = TK^*_{IC}$, K^*_{IC} = 100 MPa√m). Excellent agreement was found between these predicted and actual experimental K_{IC} values.

5.2 Hot Work Tool Steels

As in any other hot metal forming operation, there is a standard die maintenance/correction procedure in commercial aluminum extrusion. Extrusion is carried out at an optimum chamber temperature in the range of 300-600ºC. After a prescribed number of billets have been extruded, the die undergoes a cycle of caustic cleaning, nitriding and polishing. Because of the thermo-mechanical cycles during operation, and due to the periodic surface hardening in maintenance, properties of the die material do not remain constant. The current study therefore aims at determination of fracture toughness of die materials (mostly H-13 steel) undergoing different tempering temperatures and times, and being exposed to different working temperatures. Charpy tests will be carried out for a number of test specimens of H-13 steel (most commonly used tool steel in the hot aluminum extrusion industry). Three specimen temperatures (in the die operating range of room temperature to that in commercial aluminum extrusion, 300º-600ºC) will be used for each steel type (based on tempering temperature and heat treatment time).

A few significant works related to prediction of K_{IC} values of steels in the upper shelf region are found in literature. For steels in the 760-1700 MPa yield strength range, [Barsom and Rolfe, 1970], and [Rolfe and Novak, 1970] came up with the correlation

$$\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = 0.64\left(\frac{CVN}{\sigma_Y} - 0.01\right) \qquad (K_{IC}\text{: MPa}\sqrt{\text{m}},\ \sigma_Y\text{: MPa},\ CVN\text{: J}).$$

For an ultrahigh-strength aircraft steel, Ault et al. [1971] suggested the empirical correlation

$$\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = 1.37\left(\frac{CVN}{\sigma_Y}\right) - 0.045 \qquad (\text{MPa}\sqrt{\text{m}},\ \text{MPa},\ \text{J}).$$

Correlations reported by [Van der Sluys et al., 1983], [Witt, 1983] and [Kussmaul and Roos, 1984] for reactor pressure vessel steels are:

$$\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = 0.893\left(\frac{CVN}{\sigma_Y}\right) - 0.0291, \qquad (\text{MPa}\sqrt{\text{m}},\ \text{MPa},\ \text{J})$$

and

$$\left(\frac{K_{IC}}{\sigma_Y}\right)^2 = 1.23\left(\frac{CVN}{\sigma_Y}\right) - 0.0061 \qquad (\text{MPa}\sqrt{\text{m}},\ \text{MPa},\ \text{J}).$$

We can thus see that for both medium-strength and ultrahigh strength steels, the correlations are of the form

$$\left(\frac{K_{IC}(T)}{\sigma_Y(T)}\right)^2 = \alpha\left(\frac{CVN(T)}{\sigma_Y(T)}\right) - \beta. \qquad (1)$$

K_{IC}, *CVN* and σ_Y are all functions of temperature (T). The proposed prediction strategy for hot work tool steels is based on the hypothesis that the *CVN*-K_{IC} correlation is of the form given by (1). Variation of mechanical properties such as ultimate tensile strength (σ_U), yield strength (σ_Y) and Charpy impact energy (*CVN*) with temperature for tool and die steels has been reported in several works. Figure-6, for instance, is based on the data reported by [Roberts and Carey, 1980] and shows the variation of σ_U and σ_Y with temperature for two widely used hot working die steels H-11 and H-13. Experimental data at different working temperatures will also be generated in-house for H-13 steels subjected to different heat treatments (different tempering temperatures and times). Values of α and β would then be fitted through appropriate regression techniques applied to the temperature-dependent K_{IC}, *CVN* and σ_Y data and curves. For validation of the proposed correlation method, actual temperature-K_{IC} data from experiments such as that shown in Fig-7 will be used.

Additional data has been collected from studies on T_o reference temperature by Joyce and Tregoning [2001], on oil-hardening tool steels by [Hou and Hwang, 1996], on electrically discharged machined die materials by [Majid and Musa, 1998], on tool materials in metal forming by [Watkins, 1977], on tool and die steels by [Kirk,1977], on metallurgy and heat treatment of tool steels by [Wilson, 1975], and on hot work tool steels by [Unterweiser et al., 1982].

6. CONCLUDING REMARKS

In the first part of the paper, a literature review has been carried out covering the following areas: fracture toughness (K_{IC}) testing and Charpy impact energy (*CVN*) testing of various medium strength, high strength and ultrahigh strength steels (especially tool and die steels), effect of temperature variation on *CVN* and K_{IC}, transition temperature behavior in temperature-*CVN* and temperature-K_{IC} studies, empirical correlations between *CVN* and K_{IC}, and relationships between impact-energy and fracture-toughness transition-temperatures.

The second part of the paper reports the outline of an ongoing investigation of material properties (through Charpy impact tests, axial loading fatigue tests, and surface hardness measurements) of tool steels (especially H-13) subjected to heat treatment at different tempering temperatures and times, to be tested at different working temperatures. Empirical data for tool and die steels has also been collected from published literature. Based on impact energy data to be generated in-house and that gathered from published sources, a universal strategy has been proposed that will be used to develop a *CVN*-K_{IC} correlation applicable to tool steels subjected to different tempering times and temperatures, operating at different working temperatures. Strategies for temperature-K_{IC} curves valid for both lower-shelf and upper-shelf regions have been discussed.

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ACKNOWLEDGEMENTS

The authors acknowledge the support of King Fahd University of Petroleum and Minerals through the research project FT/2001-19 for this work.

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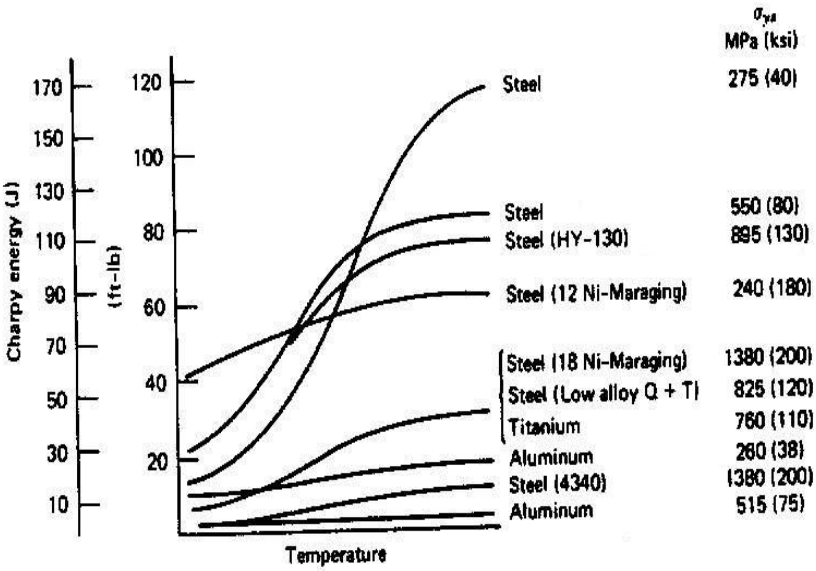

Figure-1 Transition behavior evidenced from variation of Charpy impact energy against temperature for several engineering alloys [Hertzberg, 1996].

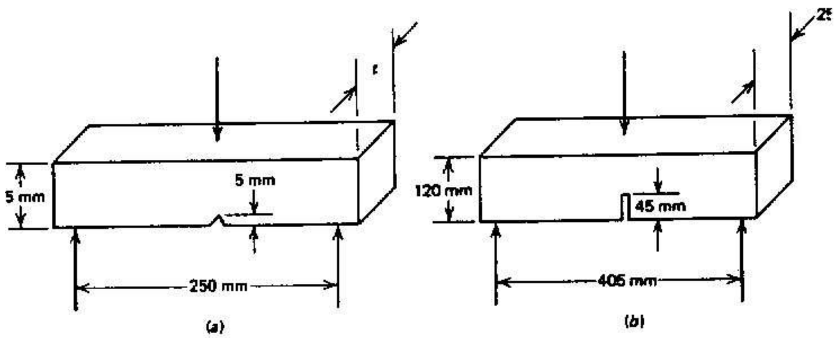

Figure-2 (a) Drop-weight tear test (DWTT) specimen with shallow notch pressed into bar; (b) Dynamic tear test (DT) specimen with machined slot introduced into titanium-embrittled electron beam weld [Hertzberg, 1996].

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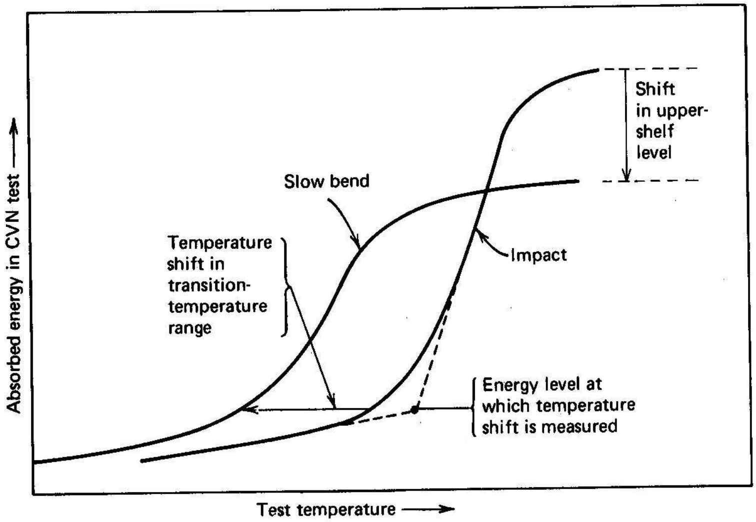

Figure-3 Impact energy versus test-temperature, showing shift in transition-temperature due to change in strain-rate [Barsom and Rolfe, 1970].

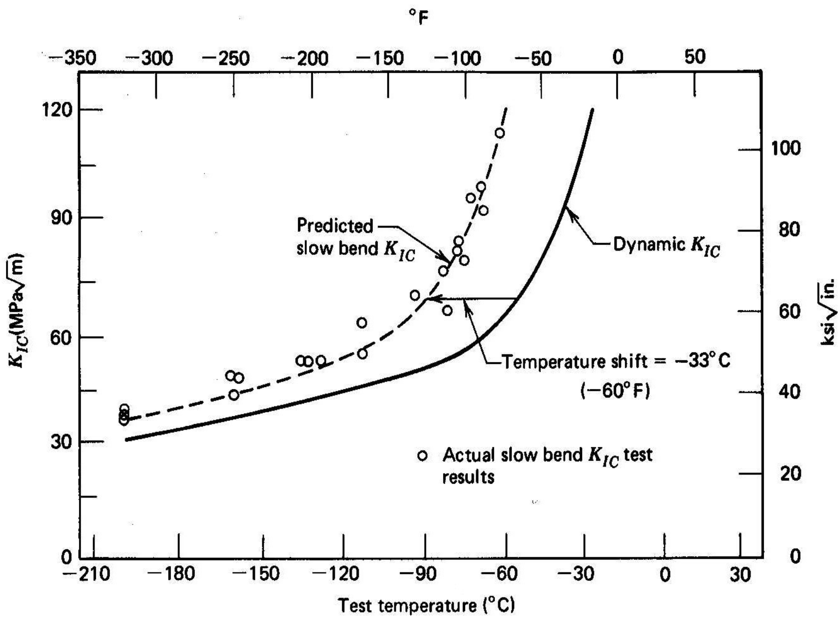

Figure-4 (a) Use of *CVN* test results to predict the effect of loading rate on K_{IC} for strain-rate sensitive A517-F steel [Barsom and Rolfe, 1970].

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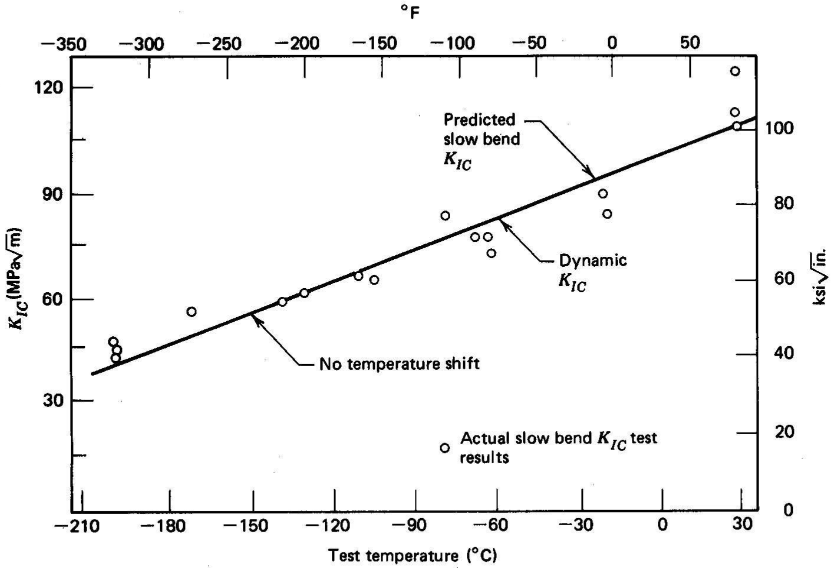

Figure-4 (b) Prediction of loading rate effect on K_{IC} for high-strength 18Ni (250) maraging steel with marginal strain-rate sensitivity [Barsom and Rolfe, 1970].

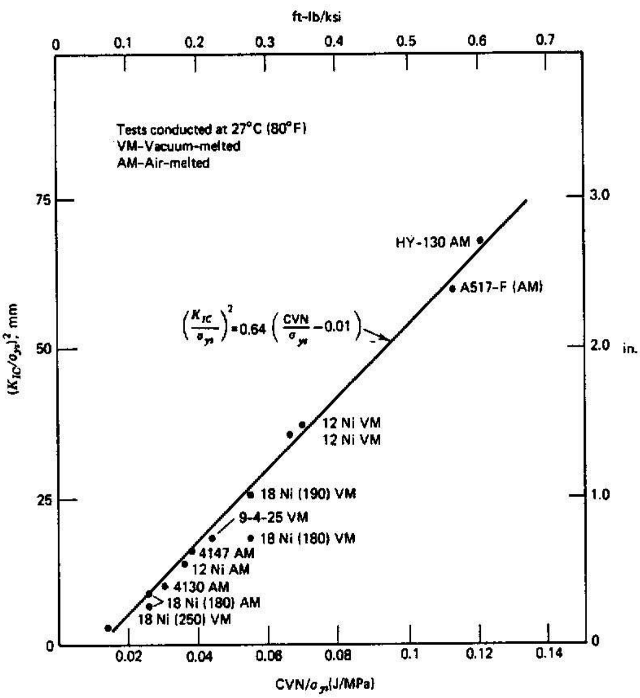

Figure-5 Relationship between K_{IC} and *CVN* values in the upper-shelf region [Barsom and Rolfe, 1970].

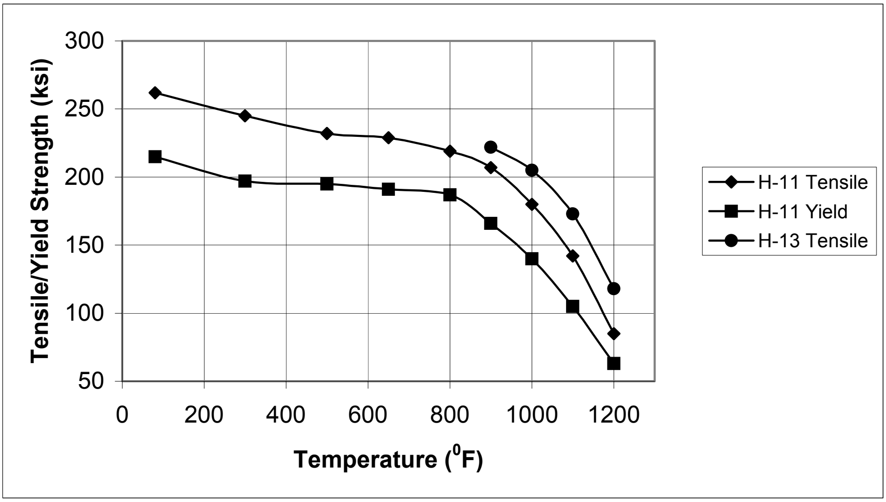

Figure-6 Variation of tensile strength (σ_U) and yield strength (σ_Y) with temperature for H-11 and H-13 hot work tool steels.

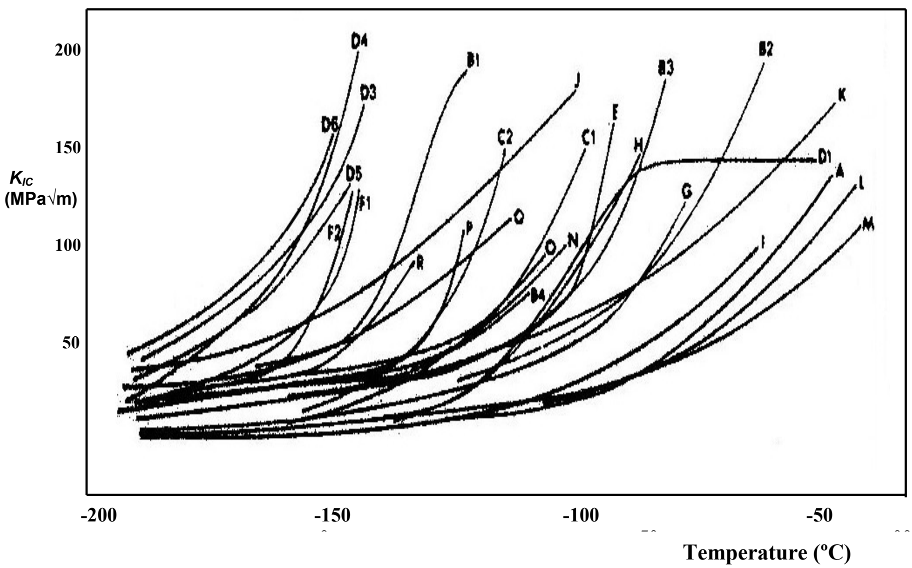

Figure 7 Variation of K_{IC} with temperature for various steels studied by Marandet and Sanz [1977].