FRACTURE TOUGHNESS OF AISI D6 TOOL STEEL AS RECEIVED AND WITH HEAT TREATMENT

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ABSTRACT

AISI D6 is an alternative tool steel used as die and punch in blanking, piercing and cold forming processes. Tooling service life is limited by plastic deformations, wear and rupture due to the presence of high stresses and cracks. Present work evaluates the critical stress intensity factor K_{IC} of AISI D6 tool steel with and without heat treatment, using the three point bending test of a notched beam or SENB specimen. Initially, a pre-crack was performed by fatigue in the notched specimen assembled in a pre-cracking mechanical equipment developed in laboratory. The fracture toughness tests were carried out in SENB specimen according to the ASTM E 399 standard. The Linear Elastic Fracture Mechanics approach was used to calculate fracture toughness of D6 tool steel heat treated and the Compliance Method of Non-linear Fracture Mechanics was utilised for calculating fracture toughness of D6 tool steel as received. The material microstructures were characterised by micrographs in an optical microscope and the ruptured surface was examined by SEM photographs. The obtained fracture toughness medium values K_{IC} were 25.9 $MPam^{1/2}$ and 44 $MPam^{1/2}$ respectively for AISI D6 heat treated and as received, indicating a decrease in ductility due the heat treatment. Although, yield stress has increased 40% . The different fracture mechanisms are also shown.

1. INTRODUCTION

Metal forming processes as sheet metal blanking, piercing, cold forging and cold deep drawing are performed using high strength tool steels. These metal forming operations requires steels of high tensile and compression yield strength to resist plastic deformations at localised stress concentration points in the tooling. Tool materials are required also to have high resistance to wear, to dynamic loading , to thermal shock and to fracture due to the presence of micro-cracks at surface and inside the bulk. However, the presence of defects or micro-cracks at surface or inside materials is inevitable and is necessary to verify if they are stable or not. These micro-cracks are originated in the raw material processing , in the heat treatment processes and in machining operations. Therefore, the material ability to sustain stable micro-cracks under loading is of major concern in tool design and in tool life service evaluation. Engineers and scientist have to know how to improve tool materials' performance under high stresses and wear. To accomplish this study, the approach of the Linear Elastic (LEFM) and Non-linear Fracture Mechanics (NLFM) and its limitations is pertinent and of great importance.

Generally, in order to apply the Fracture Mechanics approach to steels, it is necessary to characterise the type of material fracture behaviour, brittle or ductile fracture, and to determine the parameters that govern the tensile fracture behaviour or the resistance to crack propagation, as for example the stress intensity factor K_I , the energy of fracture G_C and the critical crack tip opening displacement $CTOD_C$.

AISI D2 tool steel has a high alloy content and is generally recommended as tool and die material for blanking and piercing [1]. Alternatively, AISI D6 tool steel has similar high mechanical properties and is a potential material for these applications, although its chemical composition is diverse as seen in table 1. Besides yield stress and wear resistance, fracture toughness is another relevant property required for a good tooling.

Table 1. AISI D2 and D6 tool steels chemical compositions (ASTM A 681).

Tool Steel	%C	%Mn	%Si	%Cr	%V	%W	%Mo
D2	1.40~1.60	0.10~0.60	0.10~0.60	11.00~13.00	0.50~1.10	-	0.70~1.20
D6	2.00~2.25	0.20~0.60	0.20~0.40	11.00~13.00	0.15~0.30	0.80~1.25	-

Obs.: Maximum content of elements S = 0.030% and P = 0.030%.

The production of tool steel can follow the conventional route or the powder metallurgy processing [2]. The conventional metallurgy route of steel is melting, casting, hot working and heat treatment. These different manufacturing processes of tool steels can lead to variations in the mechanical properties of the final product. Thus, it is necessary to investigate the influence of processing conditions in the mechanical properties and in the fracture mechanisms of tool steels.

The aim of present work is to develop an appropriate fracture test methodology and to obtain experimentally the fracture toughness of AISI D6 steel as received and with a specific heat treatment. Therefore, the focus is to investigate the influence of the heat treatment on fracture toughness and to examine the associate fracture mechanisms.

2. FRACTURE TOUGHNESS TEST METHODS

Fracture Mechanics approach applied to steels requires initially the characterisation of the fracture behaviour type, brittle or ductile fracture, and then to use the appropriate methodology to obtain experimentally the parameters that govern the tensile fracture behaviour or the resistance to crack propagation, as for example the stress intensity factor K_I , the energy of fracture G_C and the critical crack tip opening displacement $CTOD_C$. Brittle behaviour requires the Linear Elastic Fracture Mechanics approach, whereas ductile fracture requires the Non Linear Fracture Mechanics method to obtain the R-curve behaviour and determine the crack resistance parameter K_R [3].

The state-of-the-art in Fracture Mechanics applied to metal has shown a various types of specimens and methodologies to experimentally investigate metals fracture behaviour. Therefore, it is relevant to search, among the existing ones, the appropriate methodology for fracture toughness tests to calculate experimentally the fracture toughness K_{IC} and also G_C parameters that characterise the resistance to crack propagation in tool steels. For example, the plain strain test conditions as in the compact tensile specimen C.T., the three point bending test of prismatic notched beam or SENB specimen for determining fracture parameters as K_{IC} , K_R and $CTOD_C$ [4].

2.1 The Three Point Bending Test of Prismatic Beam

An appropriate methodology for fracture test of brittle tool steel aimed at determining the fracture toughness parameters K_{IC} is based on the ASTM E 399 standard [5]. It relies on the linear elastic fracture mechanics methodology and is carried out by loading a SENB specimen as seen in figure 1. The specimen geometry utilized is the prismatic beam type with a lateral notch situated in the middle of beam and opposite to the load application point. Before testing, a pre-crack at the notch tip is slowly generated by fatigue, using a pre-cracking equipment that applies a cyclic loading in a three point bending configuration, see figure 1.

Following, the specimen is statically loaded in a three point bending test to obtain a plot of load P versus crack mouth openning displacement (CMOD) . From the plot obtained, the critical load P_Q is identified, according to the procedure in ASTM E 399. The fracture toughness for SENB specimen for LEFM is given by:

$$K_Q = \frac{P_Q}{b\,h} F\left(\frac{a}{h}\right) \tag{1}$$

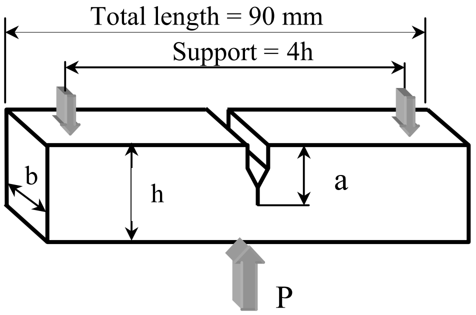

Figure 1. Schematic of SENB specimen test.

where K_Q is the preliminary toughness parameter and F(a/h) is the geometric factor [6] ,

$$F\left(\frac{a}{h}\right) = 6\sqrt{a}\;\frac{1{,}99 - \frac{a}{h}\left(1 - \frac{a}{h}\right)\left(2{,}15 - \frac{3{,}93a}{h} + 2{,}7\left(\frac{a}{h}\right)^2\right)}{\left(1 + 2\frac{a}{h}\right)\left(1 - \frac{a}{h}\right)^{3/2}} \tag{2}$$

The determination of K_Q validity for fracture toughness K_{1C} requires that the specimen thickness $b > 2.5\ (K_Q/\sigma_o)^2$, where σ_o is the yield stress, P_{max} / P_Q must be less than 1.1 and the total crack length a/h must be between 0.45 and 0.55.

On the other hand, for ductile fracture behaviour, the load versus CMOD curve is non-linear and the NLFM approach has to be used. The R-curves, that express a material fracture toughness property that is specimen geometry independent, have to be obtained. Using the concept of stress intensity factor, the resistance of crack to grow or fracture toughness parameter K_R as a function of a slow-stable crack growth can be determined, i.e., the R-curve plot. The fracture toughness K_R for SENB specimen is given by:

$$K_R = \frac{P}{bh}\,F\left(\frac{a}{h}\right) \tag{3}$$

This method relies on ASTM E 561 standard [7] and requires the indirect determination of the instant effective crack size a by the compliance method. The ratio a/h is obtained from [6],

$$b.E.\frac{V}{P} = 24\,g\left(\frac{a}{h}\right) \tag{4}$$

where E is the elastic modulus, V is the CMOD, P is the load and $g(a/h) = (a/h).V_1$

$$V_1\left(\frac{a}{h}\right) = 0{,}76 - 2{,}28.\left(\frac{a}{h}\right) + 3{,}87.\left(\frac{a}{h}\right)^2 - 2{,}04\left(\frac{a}{h}\right)^3 + \frac{0{,}66}{\left(1 - \frac{a}{h}\right)^2} \tag{5}$$

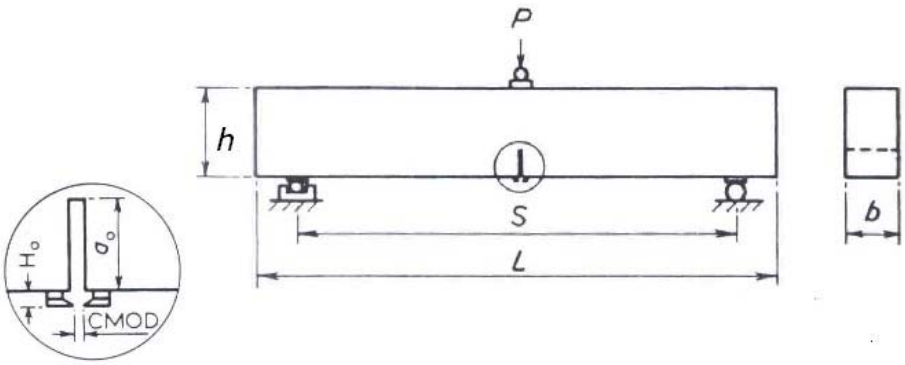

Figure 2. Three point bending test in a notched prismatic beam and its geometry:
S = 88 mm ; L = 90 mm ; b = 11 mm ; h = 22 mm, $a_o \sim 4$ mm; H_o= 2 mm.

3. MATERIALS AND EXPERIMENTAL PROCEDURES

Manufacturing the SENB specimen follows the ASTM E 399 specifications and presents three main dimensional characteristics: total crack length (a) to be pre-generated by fatigue, thickness (b) and high (h); being h=2b and a/h= 0.45 to 0.55. Figure 2 shows the SENB specimen with the main dimensional values. Initially, a groove with depth of 3 mm has been machined in the middle section of the specimen and later another groove of 1 mm depth by 0.3 mm width has been performed by wire electro-erosion machine at the bottom of the initial groove in order to guarantee the generation of a perpendicular crack. After that, the specimen was assembled in the pre-cracking machine and a fatigue crack was grown by cyclic three point bending. The applied load was regulated through the adjustment of the beam central deflection, in order to avoid premature rupture. The total crack length had to be between 9.9 mm and 11 mm. Two lines in the specimen lateral face were drawn to monitor visually the crack length during the pre-cracking operation.

Following, the SENB specimen was assembled in a universal tensile testing machine equipped with a load cell of 2 ton capacity, made EMIC. The load was applied statically by the punch which displacement velocity was set to 0.05 mm/min. The crack mouth opening displacement CMOD was monitored by a clip gauge attached to specimen by a knife, see figure 2. A plot of load versus CMOD was obtained and the fracture toughness calculated through equations 1 and 3.

AISI D6 tool steel was tested in two conditions : as received and with heat treatment. The heat treatment was quenching followed by two tempering process. For each condition, 10 specimens have been prepared. However, some have ruptured in the pre-cracking operation. Table 2 below present the heat treatment and the mechanical properties.

In figure 3 and 4 below the microstructure of AISI D6 is observed through the micrographs taken from optical microscope. The presence of chromium carbide in the ferrite matrix is clearly noted. Dispersion of small and large particles are seen in both conditions.

Table 2. AISI D6 mechanical properties and heat treatment temperatures.

Material AISI D6	Hardness HV	Elasticity Modulus E (GPa)	Yield Stress (MPa)	Quenching Temperature	Tempering Temperature
Heat treated	636	~ 210	~ 2100	950 ^oC	500 ^oC
As received	450	~ 210	~ 1500	-	-

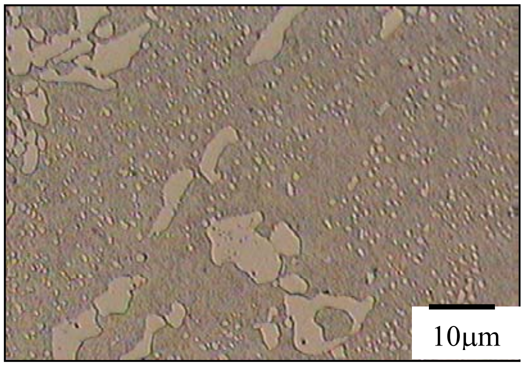

Figure 3. Micrograph of AISI D6 heat treated. Presence of Cr carbides. 200x.

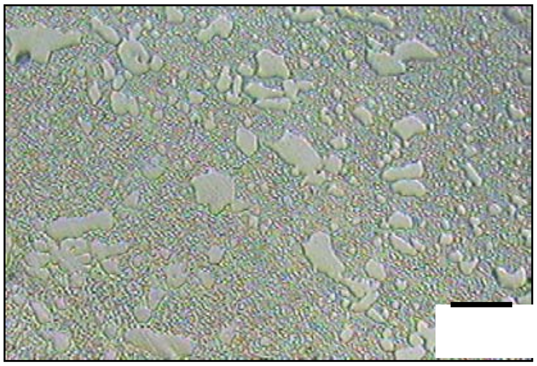

Figure 4. Micrograph of AISI D6 as received. Presence of Cr carbides. 200x.

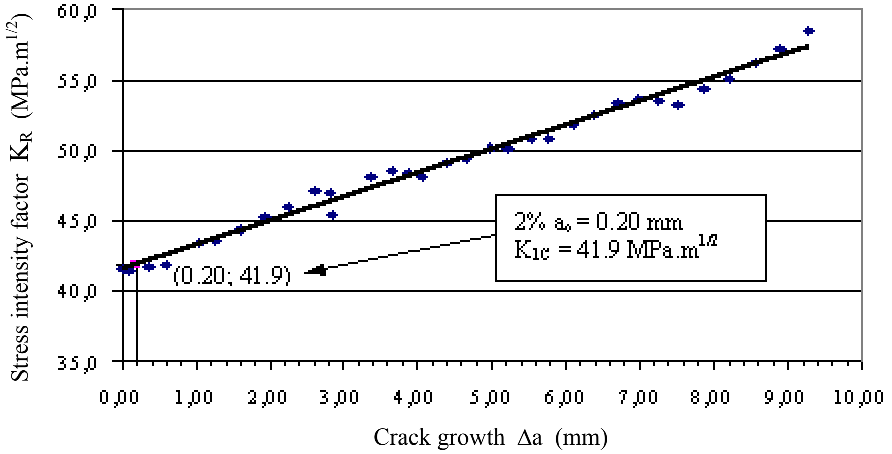

Figure 5. Stress intensity factor K_R as function of stable crack growth for AISI D6 tool steel as received . K_{IC} is at point $\Delta a = 2\% \ a_o$.

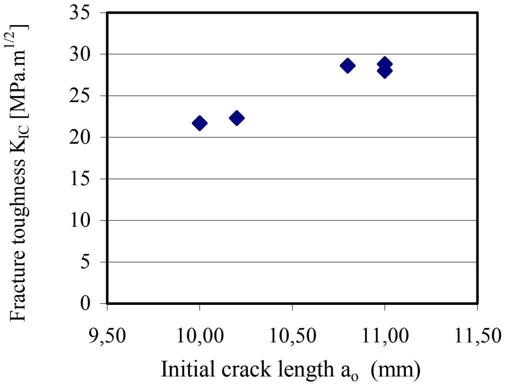

Figure 6. Fracture toughness of AISI D6 with heat treatement. $K_{IC} = 25.9$ MPam$^{1/2}$.

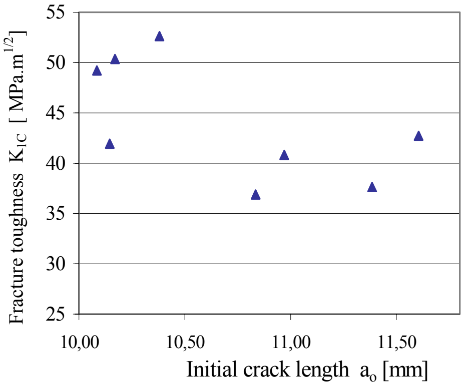

Figure 7. Fracture toughness of AISI D6 as received. $K_{IC} = 44.0$ MPam$^{1/2}$.

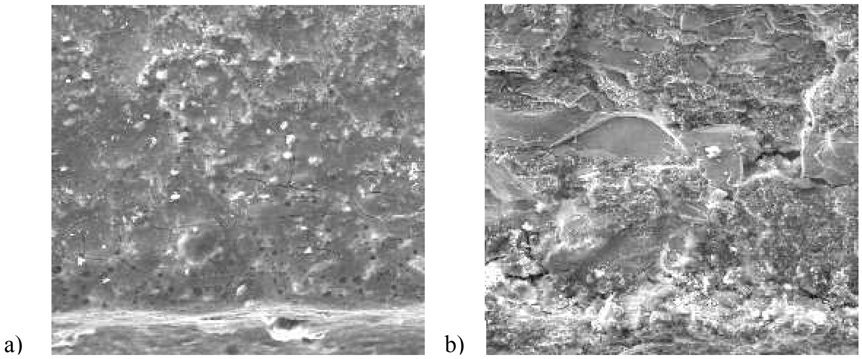

Figure 8. Fracture surface and mechanisms of AISI D6 specimen: a)fatigue and b) fast rupture. 500x.

4. RESULTS AND DISCUSSIONS

In figure 5, the experimental result of one SENB specimen in three point bending, according to the ASTM E 561 is shown. The linear increase in the stress intensity parameter K_R for ductile fracture of AISI D6 as received in function of stable crack growth is observed. The fracture toughness parameter K_{1C} was obtained from the curve at the point that correspond to the crack growth $\Delta a = 2\% \, a_o$. In figure 7, the summary of fracture toughness of AISI D6 without heat treatment is presented : medium $K_{1C} = 44$ MPa.m$^{1/2}$. Although the fracture toughness is high, the results are fairly dispersed. In figure 6 the results for AISI D6 quenched and tempered is shown : medium value is $K_{1C} = 25.9$ MPa.m$^{1/2}$. Figure 8 shows SEM photographs of the fracture surfaces.

4. CONCLUSIONS

Some conclusions can drawn about the fracture toughness of AISI D6 tool steel heat treated : fracture toughness has dropped to 25.9 MPa.m$^{1/2}$ compared with 44 MPa.m$^{1/2}$ before heat treatment. Thus, heat treatment increased the yield stress by 40% , but decreased toughness about 50%. Fracture mechanism in the fast region of AISI D6 heat treated is due to transgranular fracture.

5. ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the financial support given by CNPq and CAPES of Brazil and the University of Santa Catarina State – UDESC / Brazil.

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