INFLUENCE OF THE TEMPERATURE ON THE TOUGHNESS OF UDDEHOLM DIEVAR

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Abstract Tools for hot forming of metals, such as die casting dies, extrusion dies and forging dies, are often preheated in order to minimise temperature differences and the risk of catastrophic failure. In the present investigation the toughness of the hot-work tool steel grade UDDEHOLM DIEVAR in the temperature range 20- 400 ℃has been investigated. Quasi static K_{1c} fracture toughness testing, quasi static J_{1c} fracture toughness testing, dynamic fracture toughness testing of fatigue precracked Charpy V-notch specimens and instrumented Charpy V-notch impact testing were performed.

In the first-mentioned test the K_Q values obtained were not valid K_{1c} values due to insufficient crack length and specimen thickness.

In the J_{1c} fracture toughness test valid values were only obtained between 200 ℃and 400 ℃. Within this range the fracture toughness was independent of the test temperature. At lower temperatures it was difficult to obtain stable crack growth, the specimen cracked abrupt. This indicates that there is a decrease in toughness below 200 ℃.

The dynamic fracture toughness was also independent of the test temperature in the range 200-400 ℃. Below 200 ℃it decreased with decreasing temperature. The energy absorption at the instrumented Charpy V-notch impact test showed a temperature dependence similar to that of the dynamic fracture toughness.

Keywords: Hot-work tool steel, J_{1c} fracture toughness, K_{1c} fracture toughness, dynamic fracture toughness, instrumented impact testing, Charpy V-notch impact testing, elevated temperature.

INTRODUCTION

Tools for hot forming of metals, such as die casting dies, extrusion dies and forging dies, are often preheated in order to minimise temperature differences and the risk of catastrophic failure. In the present investigation the toughness of UDDEHOLM DIEVAR in the temperature range 20-400 $^\circ C$has been investigated. Quasi static K_{1c} fracture toughness testing according to ASTM E399 [1], quasi static J_{1c} fracture toughness testing according to ASTM E813-89 [2], dynamic fracture toughness testing of fatigue precracked Charpy V-notch specimens and instrumented Charpy V-notch impact testing were performed.

EXPERIMENTAL

K_{1C} AND J_{1C} FRACTURE TOUGHNESS TESTING

The K_{1c} and J_{1c} fracture toughness testing was performed in a 700 kN servohydraulic universal testing machine from MTS. For K_{1c} fracture toughness testing CT specimens with the thickness B=65 mm and the width W=170 mm were used. At the J_{1c} fracture toughness testing CT specimens with B=17 mm, W=34 mm and pin diameter of 6,4 mm (0,1875W) were utilised. The specimens were side grooved after the fatigue cracking. The grooves were 1,0 mm in depth and had a bottom radius of 0,25 mm. The starter notches were produced by electric discharge machining. The fatigue cracking was performed at a frequency of 6-10 Hz to a final crack length of approximately 0,53W in the K_{1c} specimens and 0,61 W in the J_{1c} specimens. The compliance method was used to measure the crack length during the testing. Afterwards it was measured in a stereoscopic microscope.

The single-specimen technique was used in the J_{1c} fracture toughness test. Six specimens were tested at each temperature. In the K_{1c} fracture toughness tests three specimens were used for each temperature level.

Both in the K_{1c} and J_{1c} test an MTS 632.65 COD gauge was used. In order to protect the strain gauges from heat and mechanical shock, contact arms made of glass were used in this type of gage. During testing at elevated temperature the specimen and clevis were encompassed by a ATS 3-zone split tube furnace.

DYNAMIC FRACTURE TOUGHNESS TESTING

Ordinary Charpy V-notch specimens were fatigue precracked in a 20 kN Amsler vibrophore at a frequency of approximately 125 Hz. The length of the cracks (including the V-notch) was 0,45-0,51W. The testing was performed in a 150 J impact testing machine from Roell Amsler equipped with instrumented tup and appropriate software. At room temperature the angle of fall was 80°and above room temperature 159,3°. After the test, the crack length was measured in a stereoscopic microscope. The software of the machine calculated three values of the dynamic fracture toughness using equations from ASTM E399 (Plain-Strain Fracture Toughness of Metallic Materials) [1], ASTM E992 (Determination of Fracture Toughness of Steels Using Equivalent Energy Methodology) [3] and ASTM E813-81 (J_{1c}, a measure of fracture toughness) [4]. The values were designated K_{1d}, K_{ds} and K_{Jd}, respectively. Six specimens were tested at each temperature.

INSTRUMENTED CHARPY V-NOTCH IMPACT TESTING

Six Charpy V-notch specimens at each temperature were tested according to EN ISO 14556 [5] in a 150 J Roell Amsler impact testing machine equipped with instrumented tup and appropriate software. Oscillations due to force interaction between the tup and the specimen make the interpretation of the force-time curves difficult. In order to obtain a fitted curve through the oscillations a filter was used (filter value 0,015).

TEST MATERIAL AND HEAT TREATMENT

All specimens were taken from the centre of a 948×435 mm bar of UDDEHOLM DIEVAR, heat E10887. DIEVAR is a recently developed hot-work tool steel grade. The direction of the normal to the crack plane in the specimens was parallel to the short transverse direction of the bar and the direction of crack propagation was parallel with the transverse direction of the bar. Such specimens can shortly be coded as S-T specimens.

All specimens were heat treated in a vacuum furnace from Schmetz GmbH. The temperature of the specimens was measured by a thermocouple placed in an extra specimen with a hole drilled to its centre. All specimens were austenitized 30 minutes at 1025 ℃and quenched in nitrogen gas. The gas pressure and fan velocity was adjusted to the specimen size so that the cooling rate was the same, irrespectively to the specimen size. The cooling time between 800 ℃and 500 ℃was 280 s which corresponds to a cooling rate of approximately 1 ℃/s or 64 ℃/min. All specimens were tempered 2*2 hours at 640 ℃to a hardness of 38±1 HRC.

RESULTS

K_{1C} FRACTURE TOUGHNESS

The following K_Q values were obtained: 195 $MPa\sqrt{m}$, 203 $MPa\sqrt{m}$ and 235 $MPa\sqrt{m}$. None of the values were valid K_{1c} values because both the crack length and specimen thickness were too small.

J_{1C} FRACTURE TOUGHNESS

Valid values were only obtained at and above 200 ℃because it was difficult to obtain a stable crack growth below 200 ℃. Moreover, as the specimens cracked abrupt, the glass arms of the extensometer were broken and must be replaced. Fig 1 shows J_{1c} and K_{Jc} versus temperature. K_{Jc} is a stress intensity value calculated from the J_{1c} value by the following equation:

$$K_{Jc}^2 = \frac{J_{1c}E}{1-\nu^2} \tag{1}$$

where E is Young's modulus and ν is Poissons's ratio.

DYNAMIC FRACTURE TOUGHNESS

Figures 2, 3, 4 show the calculated K_{1d} , K_{ds} and the K_{Jd} values, respectively, as a function of the testing temperature.

INSTRUMENTED IMPACT TESTING

The energy absorption measured from the angle of rise of the pendulum is shown in Fig 5. Figure 6 shows the energy absorption calculated from the area under the load-displacement curve. The yield load and the maximum load are shown in Fig 7 and total displacement is shown in Fig 8.

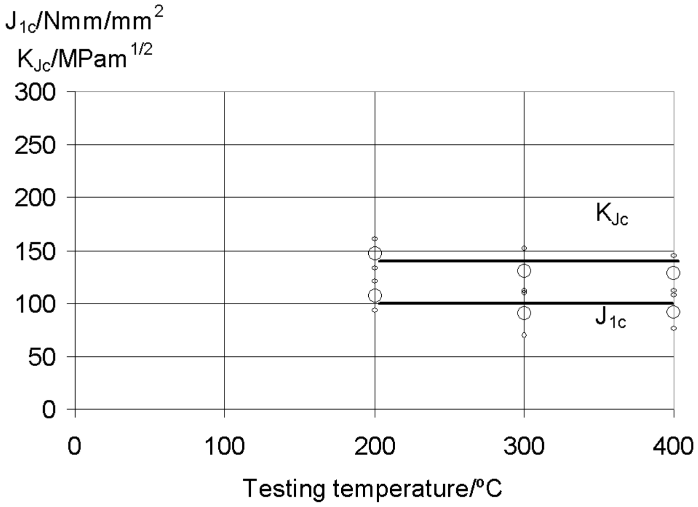

Figure 1. J_{1c} and K_{Jc} versus temperature. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value

DISCUSSION

It was no idea to make a new K_{1c} fracture toughness test with larger specimens because a force of 485-645 kN was required to break the specimens and the maximum capacity of the testing machine was 700 kN.

By means of Fig 9 one can conclude that the K_Q values obtained in the testing are larger than the real K_{1c} values. The real K_{1c} value at room temperature should consequently be lower than 200 $MPa\sqrt{m}$.

The scatter in the J_{1c} fracture toughness test was considerable. The toughness was constant in the temperature range 200-400 ℃; J_{1c} was about 95 Nmm/mm^2 and K_{Jc} about 140 $MPa\sqrt{m}$. The circumstance that it was difficult to obtain a stable crack below 200 ℃indicates that the fracture toughness decreases below this temperature.

The scatter in the K_{ds} and K_{Jd} values in the dynamic fracture test was considerable. All three measures of the dynamic fracture toughness were constant in the temperature range 200-400 ℃. Below 200 ℃all values decreased with decreasing temperature. In spite of the difference in deformation rate and the fact that Charpy V specimens do not fulfil the size criteria

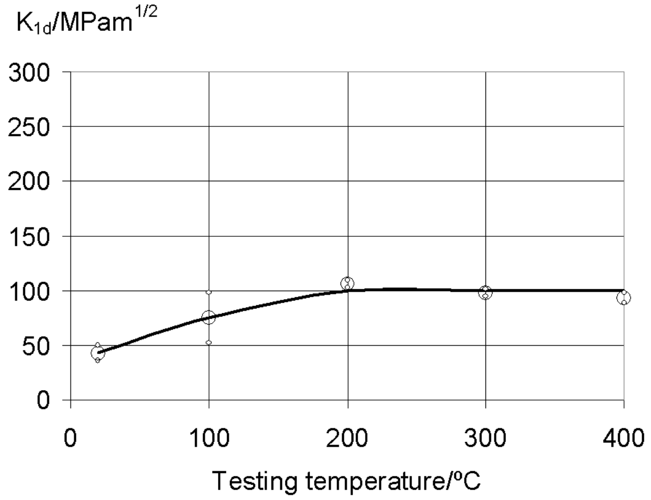

Figure 2. K_{1d} versus temperature. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value.

of ASTM E399 [1] and E992 [3] two of the dynamic fracture toughness values corresponded rather well to the quasi static K_{Jc} values calculated from the J_{1c} values. The values obtain by the equivalent energy method, K_{ds}, were most similar to the K_{Jc} values. The dynamic fracture toughness values obtained by using equations from ASTM E813 [4] seem to be too high. It is not likely that a high deformation rate gives higher toughness than a low rate.

The instrumented impact testing showed that the yield load and maximum load decreased faintly with increasing temperature. The displacement increased considerable between room temperature and 200 $℃$. In the temperature range 200-400 $℃$it was constant. The increase in energy absorption with increasing temperature is thus a consequence of a larger deflection (plastic deformation) of the specimens.

CONCLUSIONS

Dynamic fracture toughness testing with fatigue precracked Charpy V-notch specimens seems to give realistic values. However more tests must

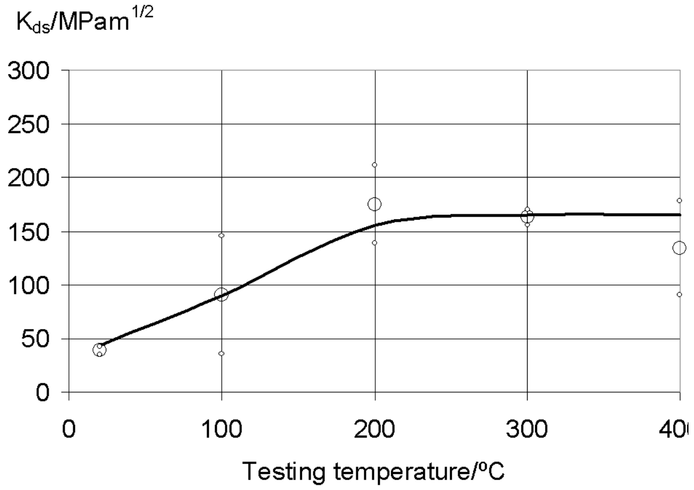

Figure 3. K_{ds} versus temperature. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value.

be made before confident conclusions can be drawn. The technique is interesting as specimen preparation and testing are considerable faster and consequently less costly than J_{1c} fracture toughness testing. In order to obtain reasonable confidence interval widths it is necessary to use more than six specimens.

It seems difficult to obtain room temperature quasi-static fracture toughness values for DIEVAR at a hardness of about 40 HRC as it is difficult to obtain stable crack growth during the J_{1c} testing. K_{1c} testing requires very large specimens. This in turn requires a high capacity testing machine with a large furnace and a COD gage with extremely long contact arms.

The energy absorption at the Charpy V-notch impact testing had the same temperature dependence as the dynamic fracture toughness.

The results of the investigation indicate that, in order to have maximum safety against catastrophic failure in hot-work tools of DIEVAR, the tool should be pre-heated to at least 200 $^\circ C$. A further increase in temperature does not seem to give any benefit in the form of higher toughness. The recommendation is valid for DIEVAR at a hardness of 38 HRC. The minimum recommended temperature for other steel grades and other hardness levels

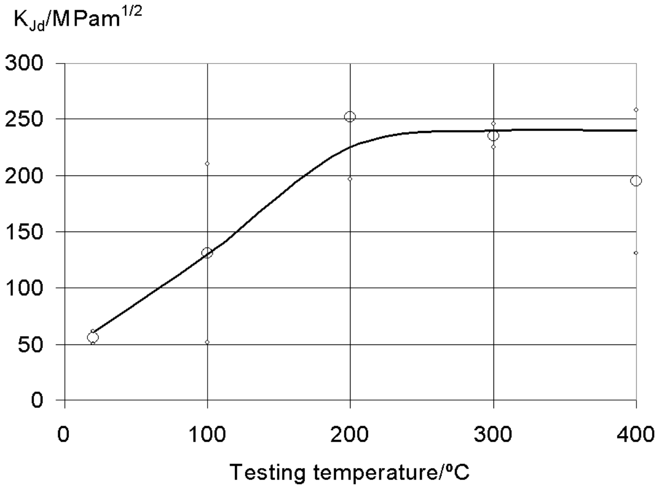

Figure 4. K_{Jd} versus temperature. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value.

may be different. 38 HRC is a rather low hardness. It is used in certain types of forging dies. The hardness of extrusion dies and die casting dies is generally higher than 38 HRC. For above mentioned reasons it may however be difficult to measure quasi-static fracture toughness at higher hardness. Stable crack growth is probably difficult to obtain during J_{1c} testing and the size requirements still makes K_{1c} testing difficult.

REFERENCES

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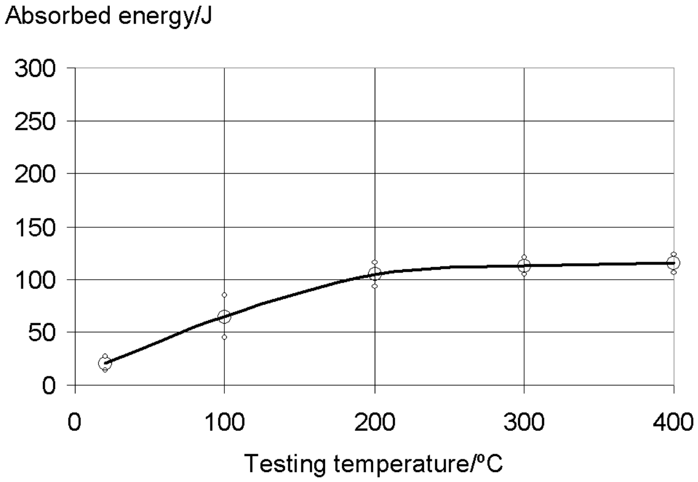

Figure 5. Energy absorbed calculated from angle of rise of pendulum. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value.

[5] Charpy V-notch pendulum impact test - Instrumented test method EN ISO 14556:2000

[6] A SAXENA, in "Nonlinear Fracture Mechanics for Engineers", (CRC Press LLC, 1998) p. 62

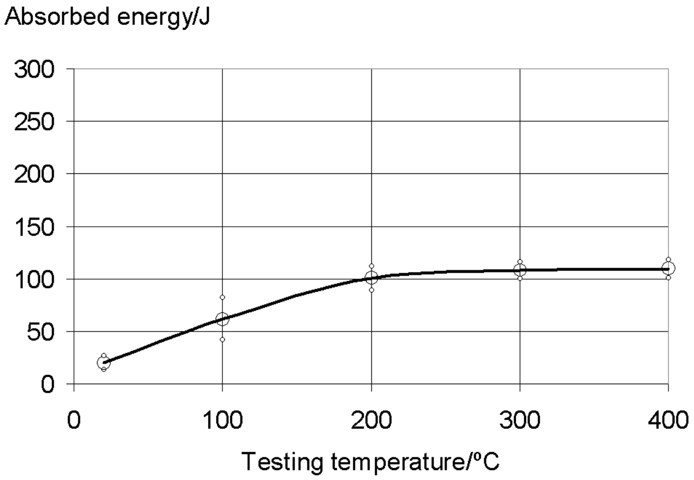

Figure 6. Energy absorbed calculated from the load displacement curves. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value.

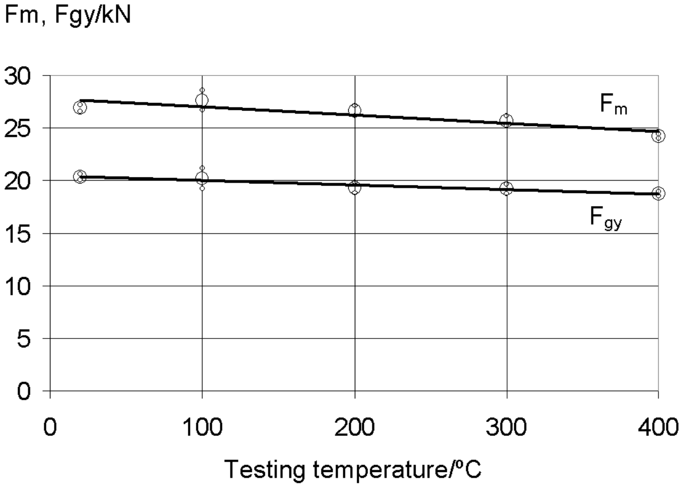

Figure 7. Maximum load, F_m, and general yield load, F_{gy}, versus temperature. The large circles indicate mean values and the small circles 95% confidence interval for the mean value.

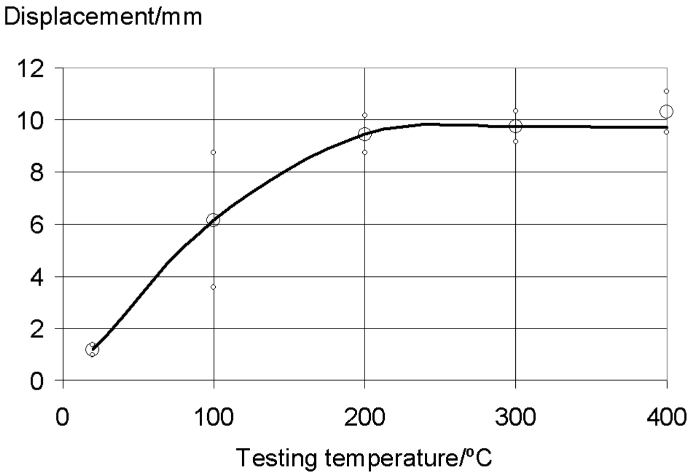

Figure 8. Total displacement versus temperature. The large circles indicate mean values and the small circles the 95% confidence interval for the mean value

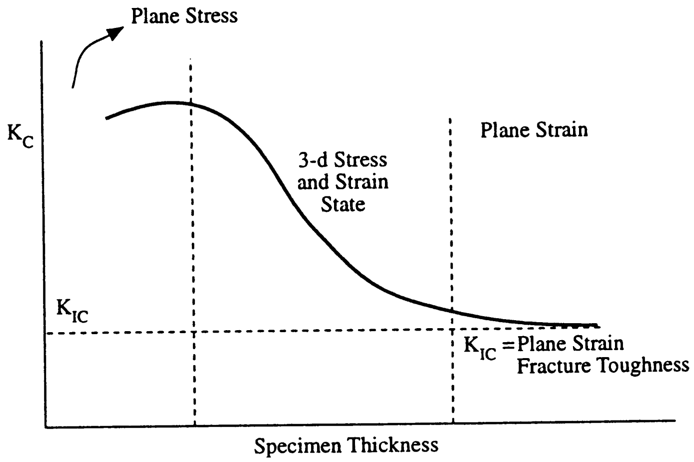

Figure 9. Relationship between fracture toughness and specimen thickness [6]