The Effect of Temperature and Loading Rate on the Fracture Toughness of Ti-6Al-4V and 7075

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Introduction

The fracture toughness of steels increases with increasing temperature and decreasing loading rate $\dot{K}$ in the ductile-brittle transition region, where the microprocesses during deformation and fracture are strongly dependent on temperature and strain rate(1). At roomtemperature, however, K_{Ic} increases, decreases or remains constant if $\dot{K}$ is increased, depending on the composition and heat treatment of the steels(2,3). Investigations of different Al- and Ti-alloys have shown that K_{Ic} can increase, decrease or remain constant with decreasing temperature (4-6). The reason for this nonuniform behavior of ductile materials is not known.

In the following it is tried to find relations between K_{Ic} and the characteristic values of tensile tests for different temperatures and loading-rates.

Results

The fracture toughness tests were performed with precracked bend specimens of the titanium alloy Ti-6Al-4V and the aluminium alloy 7075.

The experimental results are shown in Fig. 1-3. The inserted scatter regions show the range between the maximum and the minimum value of the datas (in the minimum three tests). The results of the test series for the $\dot{K}$- and the T-dependence differ, because the specimen conditions (rolling direction, microstructure) of both series were different. The results can be summarized as follows:

1. The load-crack opening displacement-curves of Ti-6Al-4V reveal only at -150 °C and -196 °C and of 7075 only above -120 °C a pop in, whereas at the other temperatures the curves were continuous.
2. K_{Ic} of 7075 is independent of T and $\dot{K}$ in the investigated ranges.
3. K_{Ic} of Ti-6Al-4V decreases first with increasing $\dot{K}$ and increases rapidly after reaching a minimum value.
4. K_{Ic} of Ti-6Al-4V has a maximum at about -120 °C.

5. Fractographic investigations with the SEM have shown that the fracture surfaces of Ti-6Al-4V had a dimple structure with a mean dimple size of 8 μm at all temperatures and loading rates. The fracture surface of 7075 reveals besides dimples also intercrystalline fracture and secondary cracks, expecially at low temperatures.
6. The evaluation of the tensile tests leads to the following results (σ_Y yield strength, δ_f true tensile fracture strain, n strain hardening exponent):

Ti-6Al-4V: σ_Y increases with decreasing T (about 60 %), n reveals a slight maximum at about -120 °C. With increasing strain rate σ_Y increases (about 15 %), n decreases (about 40 %), whereas δ_f is constant.

7075: σ_Y increases (about 20 %) and δ_f decreases (about 30 %) with decreasing temperature. With increasing strain rate δ_f decreases (about 20 %) n and σ_Y are constant.

Discussion

Because during crack propagation the plastic deformation at the crack tip is very important, it was often tried to find correlations between the fracture toughness and the results of tensile tests (7-9). Krafft (7) assumes that the crack extends, if the strain at a destinct distance from the crack tip exceeds the tensile strain at necking, which is identical with the strain hardening exponent n. This critical distance is the same as the mean diameter of the dimples d. Assuming further that the strain distribution in front of the crack tip in the plastic zone is the same as in the elastic case, K_{Ic} is given by

$$K_{Ic} = \sqrt{2\pi d}\, En \qquad (1)$$

According to Hahn and Rosenfield (8) fracture occurs, if the strain at the crack tip exceeds the true tensile strain at fracture δ_f. This strain is computed by means of the Dugdale-model. With further assumptions Hahn and Rosenfield obtain:

$$K_{Ic} = 1.56 \sqrt{2/3 \cdot \sigma_Y E \cdot \delta_f \cdot n^2} \qquad (2)$$

Fig. 4 shows a comparision between the experimental results and the fracture toughness values according to the equ. (1) and (2). For 7075 only the equ. (2) is used, because the fracture surfaces do not show a homogeneous dimple structure. To compare the results for tensile and fracture

mechanics tests for different strain (or loading) rates it is necessary to transform the $\dot{\varepsilon}$-scale into a $\dot{K}$-scale. In Fig. 4 a somewhat arbitrary factor of 10^4 was used.

For the aluminium-alloy the calculated values were - as the experimental values - independent of temperature and strain rate. For the titanium alloy the agreement between experiment and theory is not so good. The theoretical values are in the most cases higher than the experimental ones. Moreover the trend in the loading rate dependence and the temperature dependence for low temperatures is opposite. Only in the temperature range between 25 °C and about -120 °C both equations of Krafft and Hahn and Rosenfield describe the trend of K_{Ic}.

References

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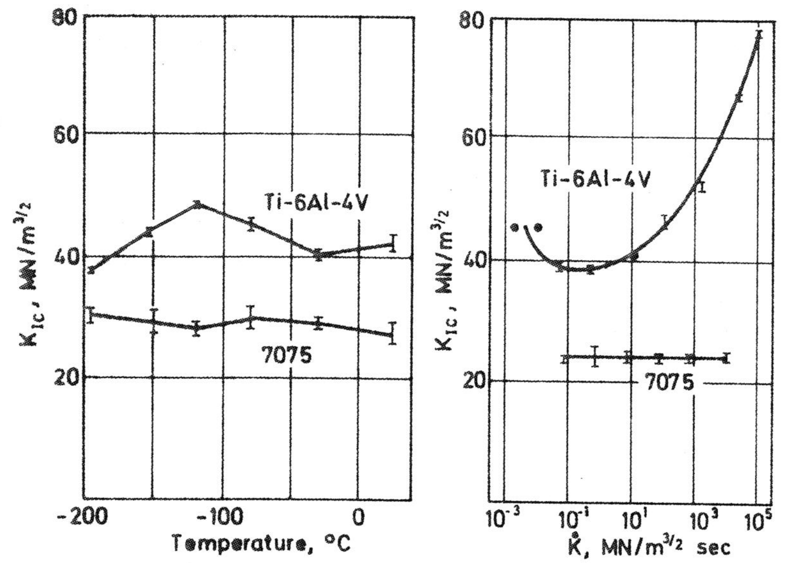

Fig. 1 T- and $\dot{K}$-dependence of fracture toughness K_{Ic} for Ti-6Al-4V and 7075

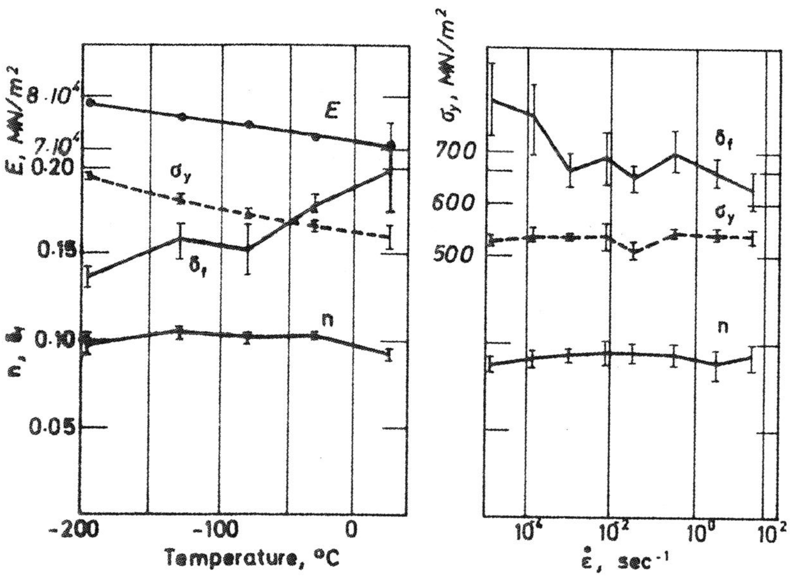

Fig. 2 T- and $\dot{\varepsilon}$- dependence of σ_Y, δ_f, n for 7075

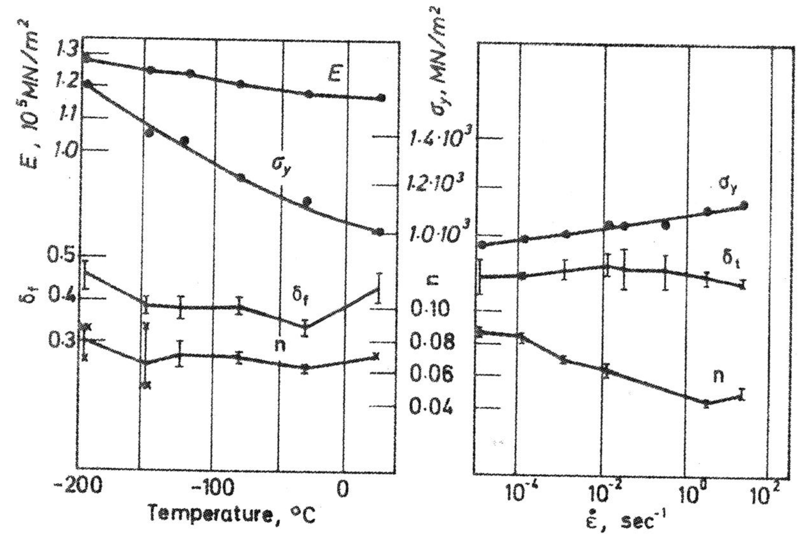

Fig. 3 T- and $\dot{\varepsilon}$-dependence of σ_y, δ_f, n for Ti-6Al-4V

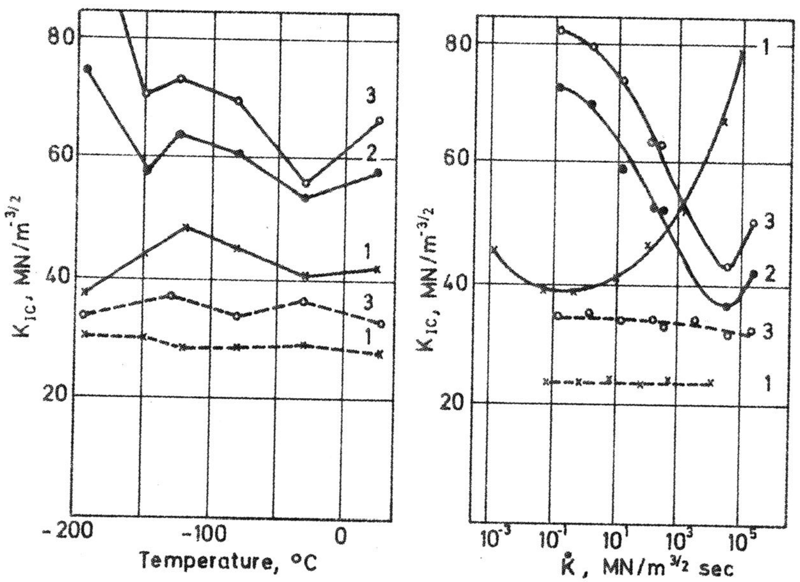

Fig. 4 Comparision between experimental (1) and calculated K_{Ic}, (2) Krafft, (3) Hahn and Rosenfield
solid lines: Ti-6Al-4V, dashed lines: 7075