PAPER REFERENCE: 1S.14

EXPERIMENTAL INVESTIGATION OF FRACTURE TOUGHNESS PARAMETERS IN QUENCHED AND TEMPERED, AND IN AUSTEMPERED 65 Si 7 STEEL

D. Pustaic,[1] F. Cajner[1] and Đ. Dobi[2]

[1]Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb,
Ivana Lučića 5, Zagreb, CROATIA
[2] Institute of Materials and Technologies, University of Ljubljana,
Lepi pot 11, Ljubljana, SLOVENIA

ABSTRACT

The results of comparative investigations of two different heat treatment procedures on the magnitude of some fracture mechanics parameteres for a characteristic kind of steel are reviewed in this paper. The experimental investigations were performed on the specimens made of 65 Si 7 steel. The processes which arise by tempering of two different microstructures, i.e. martensite and lower bainite, and their influence on fracture toughness of the material were investigated. An advantage of austempering over hardening and tempering is the achievement of bainite microstructure. The austempering procedure is much simpler in comparison with the procedure of hardening and tempering, especially in continuous heat treatment, and a product is less inclined to occurrence and accumulation of microcracks because of lower residual stresses. Steel of bainite microstructure has a greater toughness, ductility, contraction, fatigue strength and a better fracture toughness than a tempered martensite for the same steel at the equal level of strength (hardness). A bainite microstructure also gives a better resistance to thermal fatigue in comparison with martensite microstructure. The above mentioned greater values of mechanical properties refer to untempered state of bainite. In order to investigate the influence of two different heat treatment processes, i. e. hardening and tempering vs. austempering, on the value of some fracture mechanics parameters in steel, a laboratory testing of fracture toughness of steel was carried out and diagrams of loading relationships - CMOD, CTOD-Δa and J-integral -Δa were recorded.

INTRODUCTION

The aim of the performed investigations was to determine the influence of two different heat treatment procedures, i. e. hardening and tempering vs. austempering, on some mechanical properties, such as toughness, strain, contraction, strength, hardness, fatigue strength etc., of a particular type of steel, as well as the influence of these procedures on the value of some fracture mechanics parameters such as stress intensity factor (K), crack tip opening displacement CTOD and J-integral.

Austempering of steel is carried out in order to obtain the bainite microstructure which has greater toughness, strain, contraction, fatigue strength and a better fracture toughness than a tempered martensite of the same type of steel [1-6], and the equal level of strength and hardness at the same time. The bainite microstructure of this type has also a higher resistance to tempering, creeping and thermal fatigue [3,7-8].

All these advantages of bainite refer to untempered state. By tempering of bainite microstructure steel its toughness decreases and in tempered bainite it is lower than the toughness of temepered martensite [3-6]. The quoted inferior properties of bainite could have a negative influence in a hardened and tempered thicker cross-section, where, due to the cooling conditions in the core, not only martensite is formed but binite can be formed too, so in the process of tempering in the core of the product an undesirable decrease in the toughness of the structural phases mixture could occur.

The procedure of austempering is performed in the way that a product is cooled from the temperature of austenisation in a soline bath and is kept in it as long as all of the sub-cooled austenite is turned into bainite (lower or upper) and is in turn cooled in the air. The aim of austempering is to obtain a monophase bainite microstructure. In hardening and tempering, on the other hand, subsequently to austenisation, a product is cooled down in some other medium.

A basic precondition for a successful performing of austempering of steel is the choice of the adequate steel quality. It should be pointed out that this procedure of heat treatment is applicable and feasible only with elements of relatively thin cross-section (thickness of about 25 mm) and for some types of steel. It is related to a possibility of sub-cooling of austenite (the transformation of austenite should not start before the temperature of isothermal transformation is reached), or to the real curves of cooling for both the surface and the core of the product to the temperature of isothermal transformation. Consequently, the choice of the adequate steel for this procedure should be made on the basis of the right isothermal TTT diagram. It can be said that in general some non-alloyed steels are suitable for austempering and low-alloyed steels for hardening and tempering.

DESCRIPTION OF PERFORMED INVESTIGATIONS

During experimental procedures, all investigations were performed on 65 Si 7 steel specimens of the following chemical composition: 0.69% C, 1.56% Si and 0.90% Mn. Since the researches aimed to investigate the influence of various microstructural states of steel on its properties, the specimens were first submitted to heat treatment by the parameters previously determined by our own investigations [2, 8, 12, 14]. After heat treatment, photographs of microstructures of the starting conditions (prior to tempering) were taken. From the photos it is clearly seen that the specimens in the starting conditions had two different microstructures:

- by cooling down in oil the obtained microstructure was a hardened microstructure with visible plates of martensite common to the steel with this share of carbon, and its hardness was 850 HV1,
- by austempering the obtained microstructure was a microstructure of lower bainite metal base, with probably lower share of residual austenite and with hardness of 440 HV1.

These investigations comprise two groups of experiments, namely the static tensile tests (2 specimens) and tests to investigate the fracture toughness of the material (3 specimens). Hardness for all the states has been investigated as well. In the first group of tests, the specimens were loaded on stretching (tensile test). Fig. 1a shows a standard test specimen for a static tensile test. In the course of testing, the stress-strain diagrams were recorded. Investigations of mechanical parameters such as tensile strength, hardness, longitudinal strain, toughness etc, have shown that the state of austempered specimens without tempering is optimal (for the investigated temperatures of tempering) because it gives the highest longitudinal strain together with a relatively high tensile strength (hardness). In the experimental determination of fracture mechanics parameters a standard three points bending test specimen was investigated while loaded on bending in three points. Form, dimensions and load of the investigated specimens are shown in Fig. 1b.

American and British standards, projects, propositions and recommendations such as ASTM-E 399-74, [16], BSI-DD 19-72, [17], a proposal of BSI standard from 1978, [18] and ASTM-E 24, as well as ASTM-E 1290-93, [19] were used for defining the form and dimensions of the investigated specimens, for determining the loading conditions of fatigue crack initiation, the form of notch and front of a fatigue crack, the methodology of investigations, estimations of fracture mechanics parameters *K*, CTOD, *J*-integral and for determining their critical value. A fatigue crack is initiated by means of a cyclic load which has to satisfy the conditions stated by the standard.

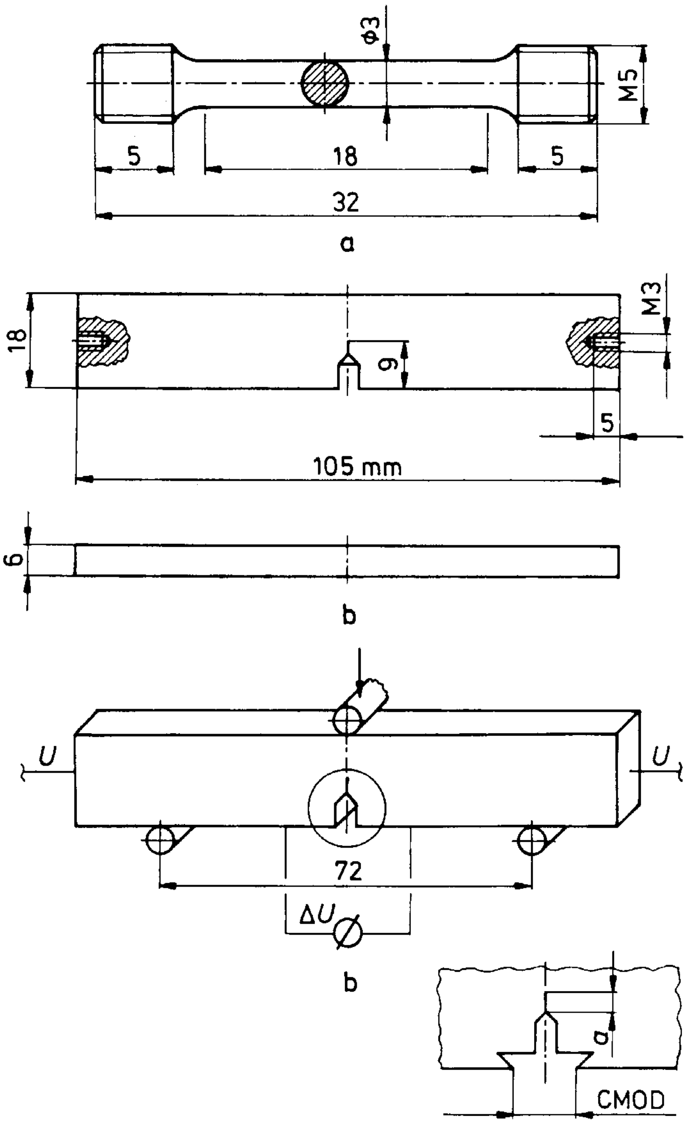


Figure 1: Form and dimensions of the tested specimens, (a) the test specimen for static tensile test, STT,(b) the three points bending specimen, 3PB according to the standard ASTM - E 399 - 74.

In the course of investigation, crack mouth opening displacement in dependence of the load on the specimen (force *F*) is measured. The measured values are recorded in the form of a diagram showing dependence of load on the crack mouth opening displacement (*F*-CMOD), Figs. 2 and 3. In the subsequent data processing the value of stress intensity factor K_Q is calculated and then its critical value K_{Ic} is determined. A similar procedure of investigation is performed for determining the critical value of the two remaining fracture mechanics parameters: *J*-integral and CTOD parameter.

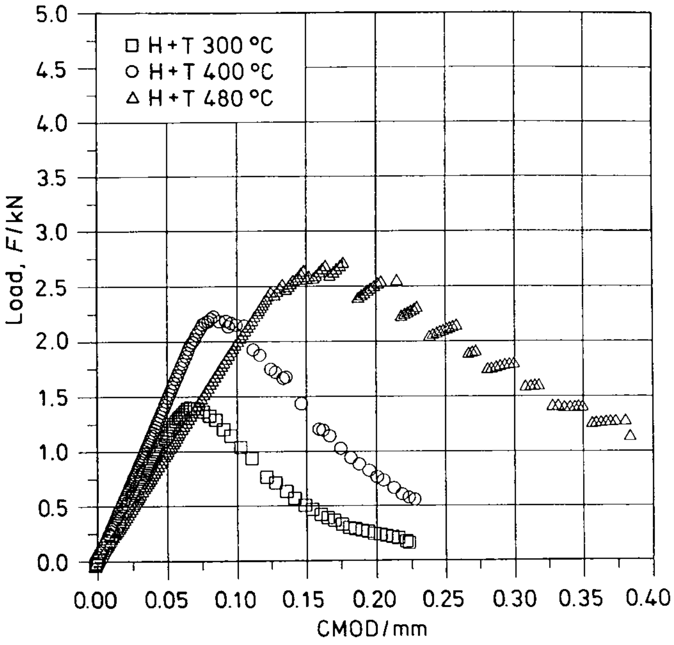


Figure 2: Dependence of crack mouth opening displacement CMOD on the force *F* for hardened and tempered specimens made of 65 Si 7 steel.

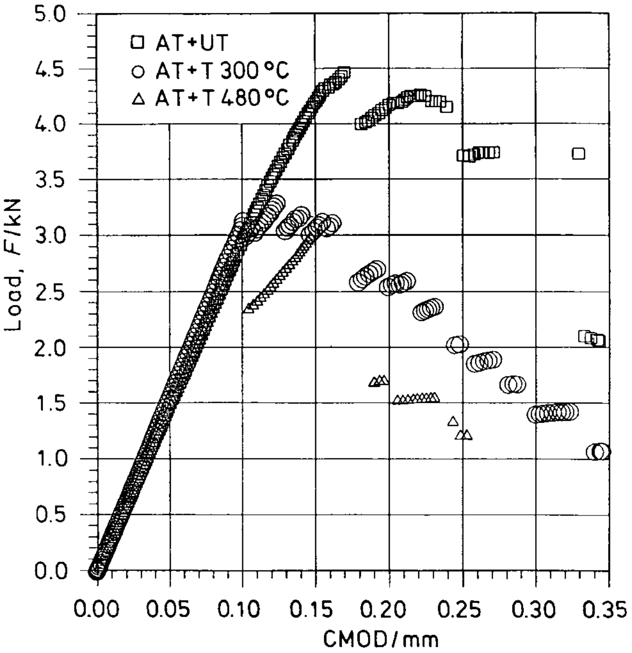


Figure 3: Dependence of crack mouth opening displacement CMOD on the force *F* for austemepered specimens, untempered and tempered, made of 65 Si 7 steel.

ANALYSIS OF THE CRITICAL VALUE OF STRESS INTENSITY FACTOR K_{Ic}

Fig. 2 shows a dependence diagram of crack mouth opening displacement CMOD on loading of the test specimen (force *F*). The test specimens involved are hardened and subsequently tempered at various temperatures of tempering ϑ_t = 300°C, 400°C and 480°C. The same dependence, but for austempered test specimens, untempered and tempered at the temperatures of $\vartheta_t = 300^{\circ}C$ and $480^{\circ}C$, is given in Fig. 3. These diagrams, namely the measured values, are the basis for estimation of the critical value of stress intensity factor K_{Ic}. All the curves in both figures show expressed maximum, so that $F_{max} = F_Q$. The force F_Q is the basic characteristic of the investigation results analysis. It is used for calculation of stress intensity factor K_Q according to the following formula [16]:

$$K_Q = \frac{F_Q\ S}{B\ W^{3/2}} Y, \tag{1}$$

where

$$Y = 2.9 \cdot \left(\frac{a}{W}\right)^{\frac{1}{2}} - 4.6 \cdot \left(\frac{a}{W}\right)^{\frac{3}{2}} + 21.8 \cdot \left(\frac{a}{W}\right)^{\frac{5}{2}} - 37.6 \cdot \left(\frac{a}{W}\right)^{\frac{7}{2}} + 38.7 \left(\frac{a}{W}\right)^{\frac{9}{2}}, \tag{2}$$

is an auxiliary function, and $S = 4W$. For the ratio $a/W = 1/2$, the value of the auxiliary function equals $Y = 2.66469$.

As for the recorded diagrams $F_{max} = F_Q$, hence follows that the ratio of these forces satisfies the condition that $F_{max}/F_Q < 1.10$, which is determined by the standard. The standard also requires that for a particular thickness of the specimen B, the calculated stress intensity factor K_Q must satisfy the following inequality:

$$a \geq 2.5\ (K_Q/\sigma_0)^2. \tag{3}$$

If this condition is satisfied, then it follows that $K_{Ic} = K_Q$. It can easily be proven that for all calculated values of stress intensity factor K_Q shown in Table 1, the condition stated in (3) is satisfied. The noted values of the force F_Q and the calculated values of stress intensity factor K_Q, or K_{Ic} are given in Table 1.

TABLE 1.

CRITICAL VALUES OF THE STRESS INTENSITY FACTOR K_{IC}
OF THE TESTED SPECIMENS HARDENED AND TEMPERED,
AND AUSTEMPERED AS WELL, MADE OF 65 SI 7 STEEL

Investigated specimen	Temperature of tempering during two hours (°C)	F_Q (N)	K_Q (MPa$\sqrt{\text{mm}}$)	K_{Ic} (MPa$\sqrt{\text{mm}}$)
Hardened and tempered specimens				
H+T 300/2	300	1400	586.21	586.21
H+T 400/2	400	2250	942.12	942.12
H+T 480/2	480	2700	1130.54	1130.54
Austempered specimens				
AT + UT	untemp.	4480	1875.87	1875.87
AT 300/2	300	3250	1360.84	1360.84
AT 480/2	480	2800	1172.42	1172.42

The analysis of the critical value of the stress intensity factor K_{Ic} investigation results shows that with higher temperature of tempering ϑ_t, higher values of the parameter K_{Ic} in hardened and tempered specimens are obtained. For example, parameter K_{Ic} is approximately twice as high at the temperature of tempering ϑ_t = 480°C / 2 hours than the one at the temperature of tempering ϑ_t = 300°C / 2 hours. A considerably improved fracture toughness is obtained in austempered specimens in comparison to hardened and tempered specimens. The best critical values of the stress intensity factor K_{Ic} are obtained by austempering without tempering and they are approximately 50% higher than the ones obtained by tempering at the temperature ϑ_t = 480°C / 2 hours, or even three times higher than the values obtained by hardening and tempering at the temperature ϑ_t = 300°C / 2 hours. The results point to the fact that by tempering of hardened steel, higher values of K_{Ic} parameter are obtained with higher temperatures of tempering, while by tempering of austempered steel the value of K_{Ic} parameter is comparably lower. This effect is even more stressed with higher temperatures of tempering.

The calculation of the critical value of the crack tip opening displacement δ_c is based upon the diagrams in Figs. 2 and 3, where the experimentally determined interdependence of loads on the tested specimen (force *F*) and the crack mouth opening displacement CMOD. All the curves have expressed an maximum. With this type of diagram, the increase in loading entails a monotonous and continuous growth of the crack tip opening until the moment when an unstable propagation of the crack starts and finally ends in collapse. The critical value of notch opening V_c is the one which corresponds to the maximal loading F_c, which is actually the total notch opening comprising the elastic component V_{el} and the plastic one V_{pl}. Critical force F_c of crack tip opening displacement is also used to determine the value of stress intensity factor *K* and its values are shown in Table 1.

CONCLUSION

Comprehensive experimental investigations carried out on the specimens made of 65 Si 7 steel had as their aim to determine the influence of two different heat treatment procedures, i. e. hardening and tempering vs. austempering, on some mechanical properties of this particular type of steel, as well as the influence of these procedures on the magnitude of some fracture mechanics parameters.

In order to determine the influence of heat treatment processes on the magnitude of some mechanical properties in steel, static tensile tests were carried out. From the results it follows that hardened specimens subsequently tempered at the temperature of ϑ_t = 480°C for 2 hours show a decrease in the value of tensile strength σ_m for approximately 450 MPa, i.e. for about 23% in comparison to the specimens tempered at the temperature of ϑ_t = 400°C. Specimens tempered at the temperature of ϑ_t = 480°C show high ductility and their maximal longitudinal strain is 8%. Austempering with a subsequent tempering at the temperature of ϑ_t = 480°C contributes to a more significant decrease in tensile strength σ_m for about 350 MPa or approximately for 20.4% in comparison to the untempered specimens, while the strain level has remained practically unchanged, i.e. very high and it amounts to 12%. The results lead us to a conclusion that it is not necessary to temper the 65 Si 7 steel after austempering because tempering does not improve some of its mechanical properties but, on the contrary, it deteriorates them (for example, tensile strength, hardness, toughness, ductility and fracture toughness).

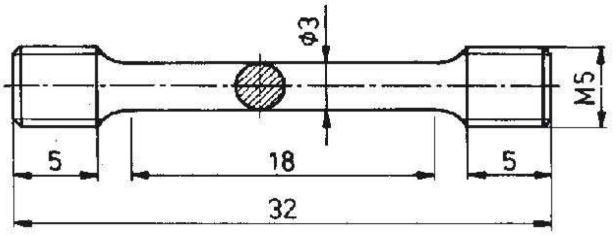
The paper also deals with a thourough analysis of parameters typical for fracture toughness of the material. The analysis of the investigation results of the critical value of stress intensity factor K_{Ic} shows that with higher temperature of tempering ϑ_t, higher values of the parameter K_{Ic} in hardened and tempered specimens are obtained. For example, parameter K_{Ic} is approximately twice as high at the temperature of tempering ϑ_t = 480°C / 2 hours than the one at the temperature of tempering ϑ_t = 300°C / 2 hours. A considerably improved fracture toughness is obtained in austempered specimens in comparison to hardened and tempered specimens. The best critical values of the stress intensity factor K_{Ic} are obtained by austempering without tempering and they are approximately 50% higher than the ones obtained by tempering at the temperature ϑ_t = 480°C / 2 hours, or even three times higher than the values obtained by hardening and tempering at the temperature ϑ_t = 300°C / 2 hours.

Finally, it can be concluded that austempered 65 Si 7 steel (temperature of austempering transformation ϑ_{at} = 330°C) in untempered state will have, together with equal hardness (tensile strength), superior values in ductility, toughness and fracture mechanics parameters (stress intensity factor K_{Ic}, critical values of crack tip opening displacement δ_{c}, magnitudes of J-integral, J_{Ii} as well as J_{Ic}) in comparison to the hardened and tempered state (temperature of tempering ϑ_{t} = 480°C) of the same type of steel. Regarding hardness and tensile strength both hardened and austempered specimens behave qualitatively in a similar way (as the temperature of tempering increases, the values of both parameters are lowered). In the same tempering conditions, ductility remains unchanged in the case of austempered specimens (and is always higher) in spite of the fact that with higher temperatures of tempering in hardened specimens ductility is improved. Regarding fracture mechanics parameters, by increasing the temperature of tempering properties of austempered specimens are deteriorated, while the ones of hardened specimens with the same temperature of tempering are improved. Such behaviour in tempering is a consequence of changes in the microstructure of steel (lower bainite and martensite) typical for the processes of tempering [1-10, 12, 14]. Because of inferior properties regarding toughness, ductility and magnitudes of fracture mechanics parameters, hardened 65 Si 7 steel should by all means be tempered at temperatures above 450°C,[12].

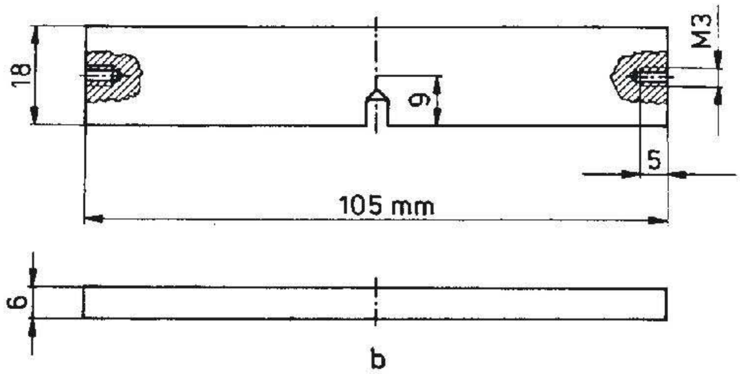
REFERENCES

1. Eysell , F. W. (1972). Die Zwischenstufenvergütung und ihre betriebliche Anwendung. *Zeitschrift für praktische Metallbearbeitung* **66**(3), 94.
2. Liščić , B. (1970). Hardening and tempering of steel in inter graduated structrure and influence of hardening and tempering on fatigue strength of spring steels under variable torsional stresses. *Proceedings of Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb,* Zagreb, Croatia, [in Croatian].
3. Rademacher , L. (1978). Anlassen von Martensit und Bainit. Vergüten oder Verspröden? *Harteärei Technische Mitteilungen*, **33**(5), 291.
4. Åkerman , J. (1980). The effect of cooling rate after austenitization on the properties of hot-work tool steels H 11 and H 13, Swedish Institute for Metals Research, 1.
5. Weckener , H. D. (1976). Die Bedeutung der Zwischenstufe bei der Wärmebehandlung von Werkzeugstählen. *Technische Berichte* **86.**
6. Hougardy, H. P. (1978). Anlassen von Martensit und Bainit. Vergüten oder Verspröden? *Harteärei Technische Mitteilungen*, **33** (5), 252.
7. Berns , H. and Wendlm F. (1987). Einfluss von Bainitanteilen auf einige Eigenschaften des Warmarbeitsstahles X 40 Cr Mo V 51. *Thyssen Edelstahl Technische Berichte*, **13,** 122.
8. Cajner, F. (1991). Influence of microstructure on thermal fatigue resistance of hot-work tool steels. *Strojarstvo, Jurnal for the Theory and Aplication in Mechanical Engineering,* **33**(5/6), 289.
9. Shiyu. H., Xiaozeng ,F. and Susan, G. (1985). The influence of the microstructures of martensite and bainite on the toughness of the steel for forging dies. In: *4th International Congress on Heat Treatment of Materials*. Berlin, 446.
10. Bhadeshia, H.K.D.H. and Edmonds, D.V. (1979). The bainite transformation in a silicon steel. *Metallurgical Transactions* A, **10A**, 895.
11. Ali, A., Ahmed, M., Hashmi, F.H. and Khan, A.Q. (1993). Incomplete reaction phenomena in high strength bainitic steels. *Metallurgical Transactions* A, **24A**, 2145.
12. Cajner, F. (1994). Contribution to research of properties of tempered martensite and tempered bainite. *Kovine, zlitine, tehnologije* **28**(6), 533, [in Croatian].
13. Bhadeshia, H.K.D.H. (1992). Bainite in steels. Institute of Materials, London.
14. Dobi, Đ., Cajner, F. and Junghans , E. (1997). Mechanical behavior of tempered martensite and tempered bainite. In: *Proc. of the 6th National Fracture Mechanics Seminarium*, Miskolc, Hungary, 210.
15. Dobi , Đ. and Junghans, E. (1996). Mechanische Eigenschaften von Schweißnähten, ermittelt an Miniflachzugproben. *DVM Tagung Werkstoffprüfung 1996*, Bad Nauheim, 561.
16. ASTM Standard E 399-74. *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials*, American Society for Testing and Materials, 1974.

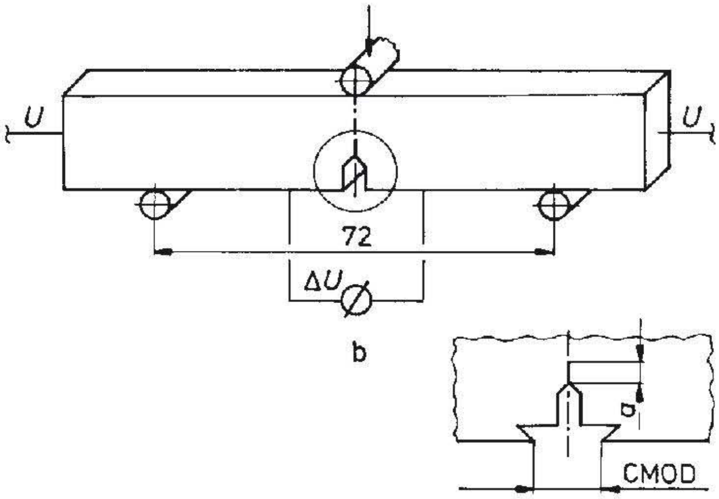
17. BSI-DD 19. *Methods for Crack Opening Displacement (COD) Testing*, British Standard Institution, 1972.
18. BSI (1978). *Draft Standard Methods for Crack Opening Displacement (COD) Testing,* British Standard Institution, 1978.
19. ASTM E 1290-93. *Standard Test Method for CrackTip Opening Displacement (CTOD), Fracture Toughness Measurement*, American Society for Testing and Materials, 1993.



a



b



b