FRACTURE TOUGHNESS OF SPOT-WELDED STEEL JOINTS

IBRAHIM SEVIM

Mersin University, Engineering Faculty, Dept. of Mechanical Eng., 33343 Ciftlikkoy, Mersin, Turkey

Received 4 February 2004, accepted 25 August 2004

Fracture toughness is one of the parameters, which are used to estimate the fatigue life of spot-welded joints. The spot-welded pair is affected by the welding zone shear stress, when it is subjected to tensile load. Repetitive loads reduce the fatigue life of the spot-welded pair, and the material splits at the spot-welded region. In this study the fracture toughness of spot welded joints has been investigated. The commercially available AISI 1010, 1030, 1040, 1050 and 50CrV4 steel sheets of 3 mm thickness were used as the test specimen for welding. Welds were performed to sheet pairs arranged as AISI 1010-50CrV4, 1030-50CrV4, 1040-50CrV4, 1050-50CrV4. The dependence of the estimated values, i.e. fracture toughness (K_{IIC}), crack lengths (a_{IIC}), and J-integral (J) to the Vickers hardness of the spot weld zone has been investigated. The fracture toughness parameter (K_{IIC}) for spot-welded steel sheets is calculated by using the formulae given in the literature. The results show that the fracture toughness, K_{IIC}, and J-integral decrease as the hardness, H, increases. The fracture toughness of the spot weld is not only dependent on the nugget diameter D, but it also depends on sheet thickness t, tensile rupture force and the hardness H.

Key words: spot-weld, stress intensity factor, J-integral, Vickers hardness, crack length

1. Introduction

Welding processes are widely used in joining the metal sheets [1]. Spot welding is commonly used process in automotive industry and for the manufacturing house appliances due to its high efficiency in processing thin metal sheets. A wide variety of metal sheets up to 3 mm thickness can be handled by the spot welding method.

The spot welded materials are exposed to different forces in different applications. The factors such as shear stress acting in spot welding zone, sheet thickness, multi-pass welding and the width of the welding zone are the important parameters

---

e-mail: isevim@mersin.edu.tr

that affect the performance of the joint. Stress intensity factor is used to express the fatigue life of spot welds. This quantity is used to predict the fatigue life of spot welding. In order to determine the fracture parameters such as the notch stress at spot-welded joints, stress intensity factor, and J-Integral, the fracture mechanics is employed. In his review on spot welding, Davidson [2] quotes the works on stress density performed by Kan [3] and Wilson and Fine [4]. Kan [3] used finite element method to obtain the stress intensity at the elastic-plastic stress zone under the influence of variable shear loads. Wilson and Fine [4] defined the stress density. Pan and Sheppard [5] discussed the formation of capillary cracks in weld zone and tried to estimate the stress intensity factors for these capillary cracks. Darwish et al. [6] investigated failure rate depending on spot-welded joints depending on welding parameters. Chang et al. [7] investigated the hardness in the interface of the plates which were welded by lap joint spot welding. For spot welded joints, the linear fracture mechanical approach is used [8]. In fracture mechanics, the stress intensity at the tip of sharp crack is quantified by stress intensity factors.

The fracture mechanics approach is commonly used to compute the stress intensity factors of the spot-weld joints under shear-tensile stress forces. The computation method for stress intensity factor using fracture mechanics is discussed briefly in following paragraphs. The weak points in microstructure of the spot weld may trigger the fracture at the welding zone. Chandel and Garber [9] formulated the strength of different spot weld microstructures (martensitic, bainitic, cold-rolled) according to the variations in the electric current, and welding cycle. Zuniga and Sheppard [10] showed that the tensile and yield strength changes with the hardness of the heat-affected zone of a zinc-coated high strength low alloy (HSLA) steel.

The main purpose in the fracture mechanics analysis is to determine the fracture parameters, e.g. stress intensity factors and J-integral. The fracture of a material is studied in three different modes [11]. These are opening mode K_{I}, shearing mode K_{II}, and tearing mode K_{III}, as seen on Fig. 1. Little work has been done in establishing stress-intensity expressions for spot-welded sheets. Pook [12] investigated the fracture behaviour of spot welds using the expressions developed by Paris, Sih, and Kassir [13, 14] based on elliptical connections, in spot-welded joints. Radaj [15] showed that the fatigue strength of spot-welded joints could be assessed considering the local stress. Zhang [16–18] showed the relation between the stress intensity factor and the J-integral for spot-welded joints. Zhang [16–18] introduced the following equations for the stress intensity factors K_{II} for spot welded joints:

$$K_{\mathrm{II}} = \frac{2F}{\pi D\sqrt{t}}, \qquad [\mathrm{MPa}\cdot\mathrm{m}^{1/2}] \tag{1}$$

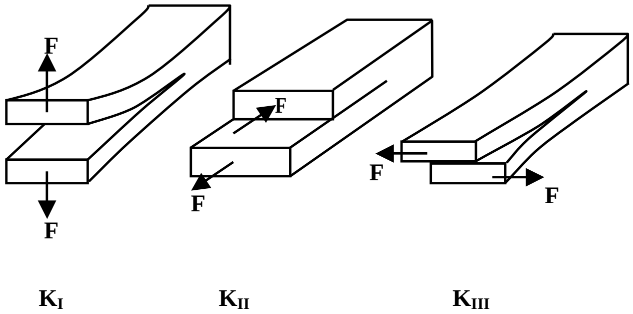

Fig. 1. Basic fracture modes: K_{I} – opening mode; K_{II} – shearing mode; K_{III} – tearing mode [11].

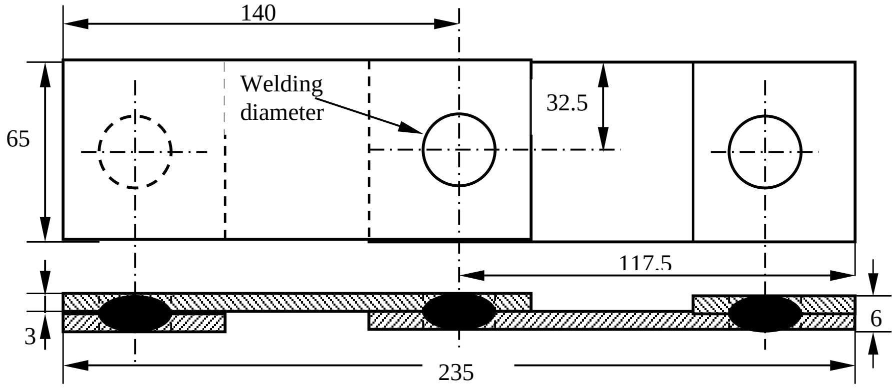

Fig. 2. The spot-welded test sample for testing in Mode II (dimensions in mm) [19, 20].

$$J = \frac{19\left(1-\nu^2\right)F}{4E\pi^2D^2t}, \qquad [\mathrm{MPa\cdot m}] \tag{2}$$

where D, t, F, ν, and E denote the spot weld diameter, sheet thickness, tensile-shear force, Poisson ratio, and Young's modulus, resp.

In this study we calculated the fracture toughness values of spot welded joints using the analytical expressions for spot welds exposed to tensile shear forces suggested by Zhang [16–18]. Moreover we developed empirical stress intensity factor expressions involving hardness of the material based on the idea that hardness is a key factor affecting the fracture of the spot weld. In the study, as a loading condition of spot welded joints the tensile shear stress was considered (Fig. 2). The equations of the Zhang [16] were used to compute the fracture toughness of spot welded joints. Also new empirical equations were developed for fracture toughness using the relation between the hardness and fracture toughness values.

2. Materials and methods

In this study, fracture toughness of spot welded joints has been investigated. Commercially available AISI 1010, 1030, 1040, 1050 and 50CrV4 steel sheets of 3 mm thickness were used in the experiments. Welds were performed to plates arranged as AISI 1010-50CrV4, 1030-50CrV4, 1040-50CrV4, 1050-50CrV4 (as in Fig. 2). Chemical compositions of the studied materials are listed in Table 1. Dimensioning of the tensile test specimens of spot welds was done according to DIN50124 as seen in Fig. 2. A 180 kV spot welding machine was used in the experiment. The electrodes were made of a copper alloy with a spherical tip of 16 mm diameter. The electrode for spot-welding machine was loaded with a constant 7.5 kN force in the same direction with the electrode. Welding currents were measured between 13 kA and 18 kA depending on welded steels. Welding process was performed for 30 welding cycles. Nugget diameter changed in the range of 8–13 mm due to changes in the welding current and the properties of the material.

The spot welded parts were tested under the tensile-shear mode as shown in Fig. 3. Tensile-shear load is taken as the maximum rupture load value. During the tensile tests, all parts were loaded at constant speed of 7 mm per minute. The chemical composition of nugget at the interface of the welded sheets is given in Table 2.

Table 1. The chemical compositions of experimental steel used in the experiments [wt.%]

Alloy	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Mo [%]	Ni [%]	Al [%]	Cu [%]	Ti [%]	V [%]
1010	0.107	0.11	0.413	0.019	0.025	–	0.003	–	0.032	0.031	0.002	–
1030	0.328	0.069	0.673	0.015	0.019	–	0.001	–	–	0.037	0.002	0.005
1040	0.402	0.247	0.82	0.012	0.028	0.025	0.001	0.003	0.014	0.032	0.001	0.003
1050	0.506	0.252	0.654	0.014	0.006	0.251	0.002	–	0.006	0.017	0.002	0.006
50CrV4	0.523	0.394	0.915	0.021	0.027	0.917	0.025	0.034	–	0.183	–	0.095

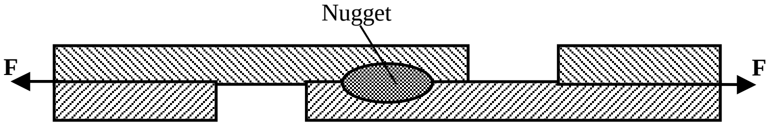

Fig. 3. The tensile-shear loading of the spot-welded test specimen [20].

Table 2. The chemical compositions of weld metal [wt.%]

Alloy pairs	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Mo [%]	Ni [%]	Al [%]	Cu [%]	Ti [%]	V [%]
50CrV4-1010	0.315	0.252	0.665	0.020	0.026	0.458	0.014	0.017	0.016	0.10	0.001	0.05
50CrV4-1030	0.425	0.231	0.794	0.018	0.023	0.458	0.013	0.017	–	0.11	0.001	0.05
50CrV4-1040	0.463	0.321	0.868	0.017	0.028	0.471	0.013	0.019	0.007	0.108	0.004	0.049
50CrV4-1050	0.514	0.323	0.784	0.018	0.017	0.584	0.014	0.017	0.003	0.1	0.001	0.050

The fracture force of the welded parts was determined from the data obtained in the tensile-shear tests. The nugget diameters were determined from the optical microscopy taken from the fracture surface of the samples, which were pulled to failure in the shearing mode. Three measurements were performed for each of the 208 samples. Mean values of the measurements were taken as nugget diameter. For the case in Figs. 2 and 3, Eqs. (1), (2) were used to calculate the fracture toughness value (K_{IIC}) and J-integral (J).

The heat-affected zone of the spot weld was ground using abrasive papers of 80–1200 meshes, and then polished with 0.3 μm diamond paste. The Vickers hardness of the polished surface was measured at every 0.5 mm applying the load of 98.0665 N.

3. Results

Sheet thickness t of the specimen was 3 mm. Nugget diameters D of spot-welds varied between 8 and 13 mm. Rupture loads of the nugget were measured to be between 10 and 24 kN. The fracture toughness value (K_{IIC}), and J-integral (J) were computed for spot welded sheets applying Eqs. (1) and (2), resp. The variation of K_{IIC} and J with the Vickers hardness HV is given in Figs. 4 and 5. As it is evident from the figures the fracture toughness and J-integral decrease with increasing Vickers hardness. The decrease is proportional to H^{-1} and H^{-2} for fracture toughness value and J-integrals, resp.

We developed the following relation between fracture toughness and hardness of spot welded sheets of the materials studied using the least squares method of curve fitting (Fig. 4):

$$K_{\mathrm{IIC}} = 147440H^{-1}. \tag{3}$$

The fracture of spot weld occurs when the applied stress intensity factor at the crack tip is higher than the critical value. In this situation the following relation can be used [19, 20]:

$$K_{\mathrm{II}} \geq K_{\mathrm{IIC}}. \tag{4}$$

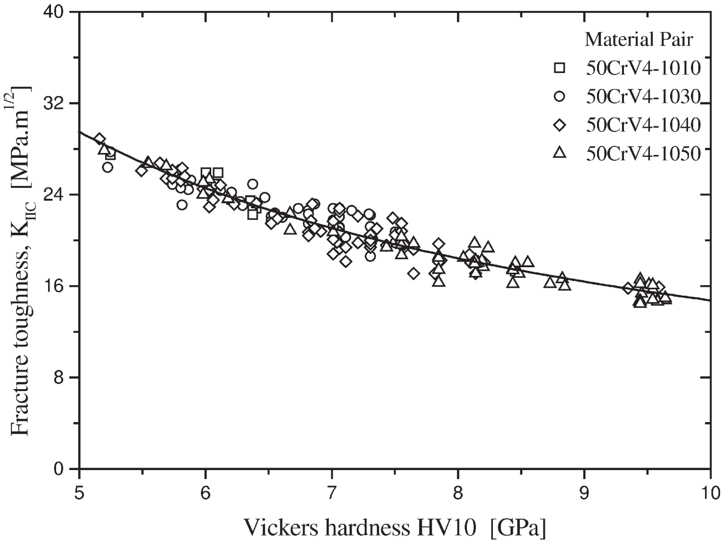

Fig. 4. Fracture toughness value for mode II K_{IIC} versus Vickers hardness HV.

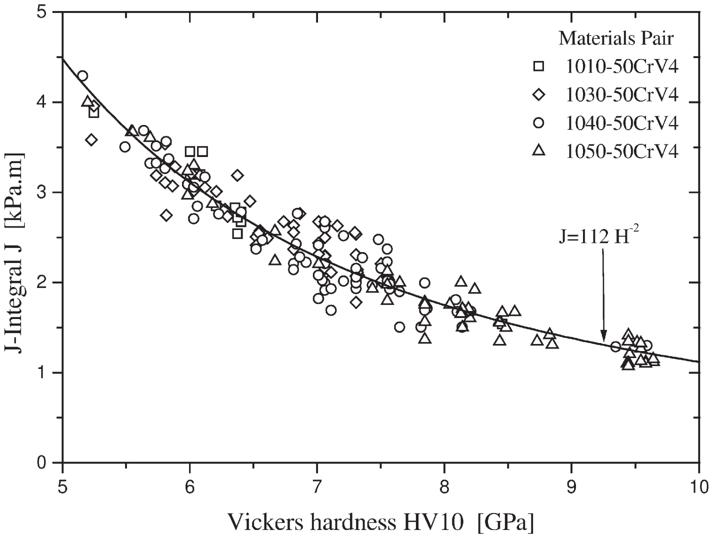

Fig. 5. J-integral, J, versus Vickers hardness HV.

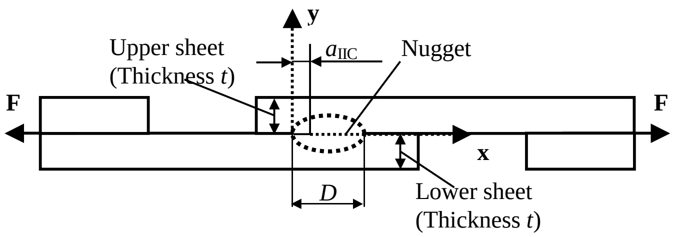

Fig. 6. Critical crack length (a_{IIC}) at spot-weld in fracture mode II.

The following expression for K_{II} was modified from the relation in the literature [21] for this study to compute the critical crack lengths:

$$K_{\mathrm{II}} = \tau\sqrt{\pi a_{\mathrm{IIC}}}, \tag{5}$$

where τ is the applied shear stress, and a_{IIC} are critical crack lengths at spot-weld in different fracture modes as shown in Fig. 6. Since the plastic deformation takes place during fracture, the applied shear stress τ is

$$\tau \cong \tau_{\mathrm{yield}} \tag{6}$$

and

$$\tau_{\mathrm{yield}} = \frac{\sigma_{\mathrm{yield}}}{2}. \tag{7}$$

The relation between the hardness and yield stress for the steel can be defined [22] as

$$H \cong 3\sigma_{\mathrm{yield}} \tag{8}$$

and by using Eq. (8), the following equations can be obtained for stress intensity factors:

$$K_{\mathrm{II}} = \frac{H}{6}\sqrt{\pi \cdot a_{\mathrm{IIC}}}\ . \tag{9}$$

Substituting (3) into (9), the following equations are obtained:

$$\frac{H}{6}\sqrt{\pi \cdot a_{\mathrm{IIC}}} = 147440H^{-1}. \tag{10}$$

Using the above Eq. (10), the critical crack lengths (a_{IIC}) can be found as

$$a_{\mathrm{IIC}} \geq \frac{36}{\pi}\left(\frac{147440}{H^2}\right)^2. \tag{11}$$

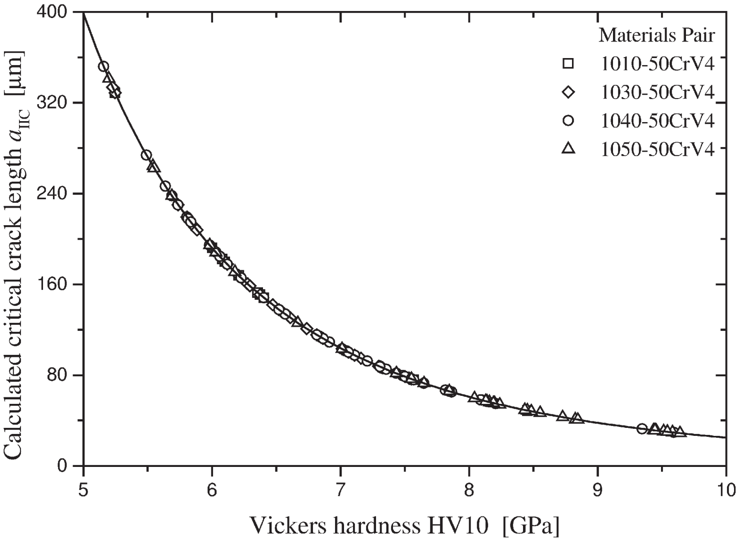

Fig. 7. Calculated critical crack length a_{IIC} versus Vickers hardness HV.

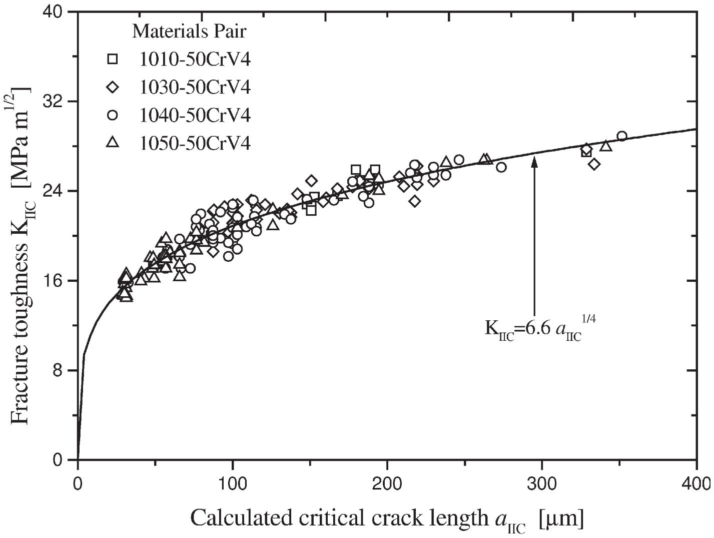

Fig. 8. Fracture toughness value for mode II K_{IIC} versus calculated critical crack length a_{IIC}.

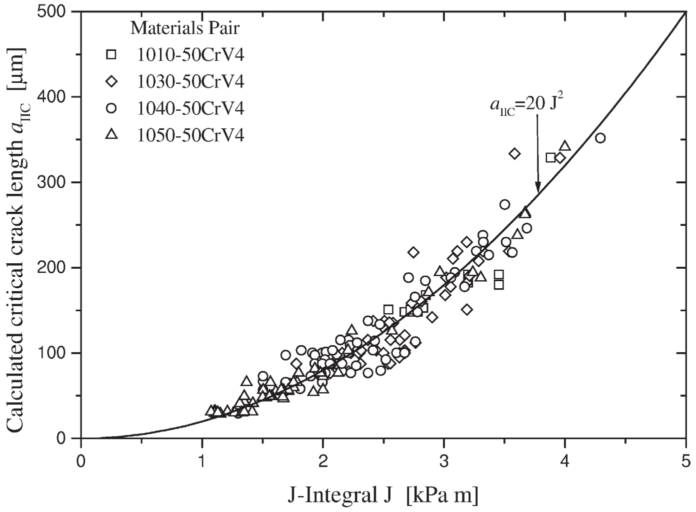

Fig. 9. Calculated critical crack length a_{IIC} versus J-integral, J.

The variation of the critical crack lengths that are computed from Eq. (11) is shown in Fig. 7. It is clear from Fig. 7 and Eq. (11) that the critical crack length becomes smaller as the hardness increases.

Fracture toughness values can be computed by using the following equation:

$$K_{\mathrm{IIC}} = 6.6 a_{\mathrm{IIC}}^{1/4} \, . \tag{12}$$

Fracture toughness values obtained from Eq. (12) are given in Fig. 8.

The critical crack length versus J-integral, which was calculated by using Eq. (2) is given in Fig. 9. Figure 9 shows that the increase in critical crack length is proportional to the square of J-integral values.

4. Discussion

The solid lines in Figs. 4–9 are obtained from the least square method. Figure 4 shows that the fracture toughness is inversely proportional with the hardness for spot-welds. The variables that affect the microstructure of the welding zone are welding current, the cycle of the current, holding time, the chemical composition of the steel sheets, and the cooling rate of the weld zone. Different microstructures arise depending on these parameters. Each particular structure has its own hardness value. The hardness at the welding zone takes high values, since an alloy microstructure is formed in the welding zone of the two different material structures

(50CrV4-steel). Nugget zone of the weld has similar properties to cast structure. Nugget zone has higher hardness than base material. Inclusions, incoherent particles and grain boundaries are probable crack initiation sites. They could also aid crack propagation and eventually lead to failure in spot welded joints. Zum Garh [22] shows that the fracture toughness decreases while the hardness increases.

5. Conclusion

Following results have been obtained for spot weld joints made of sheet samples of AISI 1010-50CrV4, 1030-50CrV4, 1040-50CrV4 and 1050-50CrV4 when the experimental data are applied as in Fig. 2:

– The fracture toughness, K_{IIC}, and J-integral, J, decrease as the hardness, H, increases. The decrease is proportional to H^{-1} and H^{-2} for fracture toughness values and J-integrals, resp.

– The hardness at the welding zone is higher than that of unaffected area which is probably due to microstructure being altered during welding.

– The critical crack length a_{C} decreases as the hardness H increases. a_{C} is the critical crack length that corresponds to critical value of stress intensity factor. The increase in critical crack length is proportional to the square of J-integral values.

– The fracture toughness of spot weld is not only dependent on the nugget diameter D, but it also depends on sheet thickness t, tensile rupture force and the hardness H.

REFERENCES

[1] KULEKCI, M. K.: Kovove Mater., *41*, 2003, p. 97.
[2] DAVIDSON, J. A.: SAE Technical Paper Series, Paper No. 830033, 1984, p. 35.
[3] KAN, Y. R.: Metals Engineering Quarterly, *16*, 1975, p. 26.
[4] WILSON, B.—FINE, T. E.: SAE Technical Paper Series, Paper No. 810354, 1981, p. 1.
[5] PAN, N.—SHEPPARD, S. D.: Engineering Fracture Mechanics, *70*, 2003, p. 671.
[6] DARWISH, S. M.—SOLIMAN, M. S.—AL-FAHEAD, A. M.: Journal of Materials Processing Technology, *79*, 1998, p. 66.
[7] CHANG, B.—YAOWU SHI, Y.—LU, L.: Journal of Materials Processing Technology, *108*, 2001, p. 307.
[8] PARIS, P. C.—ERDOGAN, F.: Trans. ASME J. Basic Eng., *4*, 1984, p. 528.
[9] CHANDEL, R. S.—GARBER, S.: Metals Technology, *1*, 1975, p. 418.
[10] ZUNIGA, S. M.—SHEPPARD, S. D.: Modeling Simul. Mater. Sci. Eng., *3*, 1995, p. 391.
[11] LAWN, B.: Fracture of Brittle Solids. Second Edition. Cambridge, Cambridge University Press 1993.
[12] POOK, L. P.: Int. Journal of Fracture, *11*, 1975, p. 173.
[13] PARIS, P. C.—SIH, G. C.: In: Symp. on Fracture Toughness Testing and its Application. Philadelphia, ASTM STP381 1965, p. 30.
[14] KASSIR, M. K.—SIH, G. C.: Int. J. Fracture Mech., *41*, 1968, p. 347.
[15] RADAJ, D.: Welding and Cutting, *1*, 1989, p. E10.

[16] ZHANG, D.: International Journal of Fracture, *88*, 1997, p. 167.
[17] ZHANG, D.: Int. J. of Fracture, *99*, 1999, p. 239.
[18] ZHANG, D.: Int. J. of Fracture, *88*, 1997, p. 167.
[19] ERYÜREK, B. I.: Study of Contact Resistance at Electrical Resistance Spot Weld. [Ph.D. Thesis]. İ. T. Ü., İstanbul, Faculty of Mechanical Engineering 1976.
[20] SEVIM, I.: Effect of Abrasive Particle Size on Wear Resistance for Abrasive Wear of Steels. [Ph.D. Thesis]. İ. T. Ü., İstanbul, Institute of Science and Technology 1998.
[21] BROEK, D.: Elementary Engineering Fracture Mechanics. Neyden, The Netherlands, Noordhoff International Publishing 1976.
[22] ZUM GAHR, K. H.: Microstructure and Wear of Materials. New York, Elsevier Science 1987.