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IHOR V. ROKACH)*

INFLUENCE OF FRICTION ON RESULTS OF AN IMPACT FRACTURE TEST

For an impact fracture test, the influence of Coulomb friction between the specimen and anvil on contact forces and dynamic stress intensity factor (DSIF) has been investigated numerically. It has been shown that friction leads to increasing of the mean tup and anvil forces and decreasing of mean DSIF. Additionally, in most cases, friction leads to increasing of the amplitude of DSIF oscillations and, in consequence, makes interpretation of the test results more complex. Simple formulae for correction of reduced by friction mean DSIF values have been proposed.

1. Introduction

Contrary to the quasi-static case, where adjustable rollers used as supports reduce effect of friction significantly, the fixed supports are usually used in dynamic tests. Thus, there is always some friction in the specimen/support contact zones during an impact test. In the literature related to the numerical modelling of an impact fracture test, the problem of friction between a specimen and anvil has not attracted much attention. From the very beginning of the impact test modelling it was clear that friction affects results of a test considerably [1]. However, detailed quantitative analysis of friction caused changes in time variation of contact forces and dynamic stress intensity factor (DSIF) is still unavailable. In this article, some results of the finite element (FE) modelling of an impact test for a wide range of specimen configurations and values of coefficient of friction are presented.

*) *Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego 7, 25 314 Kielce, Poland; E-mail:rokach@tu.kielce.pl*

2. Preliminary quasi-static analysis

Let us consider an impact specimen loaded by the striker force $F(t)$ and normal and tangential anvil forces $R_n(t)$ and $R_t(t)$, respectively (Fig. 1). In this study, the simplest form of the friction law (Coulomb law with constant sliding coefficient of friction (CoF) f) will be considered. This law assumes that $|R_t(t)| = f R_n(t)$ if there is sliding in the specimen/support contact zone and $|R_t(t)| < f R_n(t)$ otherwise.

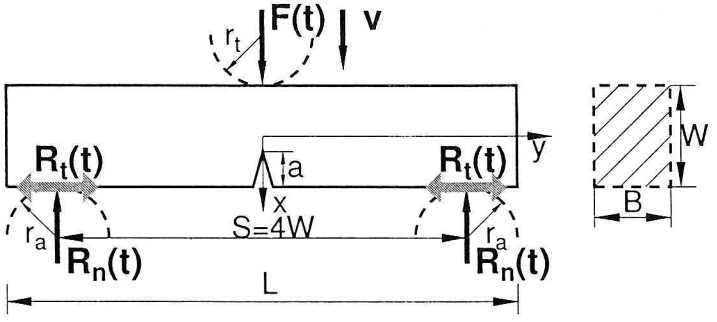

Fig. 1. Impact specimen model

For sufficiently long time after impact, transients decay and DSIF tends to quasi-static SIF for the same loading. This SIF can be considered as a result of frictionless three-point-bending (3PB) of the specimen caused by one force $F(t)$ and two forces $R_n(t)$ combined with tension or compression caused by two friction forces $R_t(t)$. Type (means compression or tension) of the additional load caused by friction depends on whether $F(t)$ grows or reduces. Both elementary beam theory analysis and FE computations show that in quasi-static case monotonic growth of the bending force (i) always causes sliding of the specimen in the specimen/support contact zone in the outside direction with respect to crack tip and (ii) corresponding friction forces act as a compressive load for the crack tip zone. Similarly, monotonic decrease of bending force causes sliding of the specimen towards the crack position and corresponding friction forces act as a tensile load for the crack tip zone. It means that in these cases $R_t(t) = -\operatorname{sign}(\dot{F}(t)) f R_n(t) \equiv -\operatorname{sign}(\dot{F}(t)) f F(t)/2$, where the dot means derivative with respect to time. Resulting quasi-static SIF $K_I^{qs}(t)$ can be calculated as superposition of known $K_I^{bend}(t)$ for 3PB [2], [3] and $K_I^{tens}(t)$ for the specimen in tension by two equal forces applied at its edge [4] at the contact zones:

$$K_I^{qs}(t) = K_I^{bend}(t,\ F(t)) - \operatorname{sign}(\dot{F}(t)) f K_I^{tens}(t,\ F(t)/2) = \\ = \frac{6F(t)\sqrt{\pi l}}{BW} Y(\lambda) - \operatorname{sign}(\dot{F}(t)) f \frac{2F(t)\sqrt{\pi l}}{BW} Z(\lambda) \tag{1}$$

where $Y(\lambda)$ and $Z(\lambda)$ are the functions of the relative crack length $\lambda = l / W$ determined in [3] and [4], respectively. Eq. (1) can be rewritten as

$$K_I^{qs}(t) = \frac{6F(t)\sqrt{\pi l}}{BW} Y(\lambda)(1 - \operatorname{sign}(\dot{F}) f g(\lambda)) = K_I^{bend}(t,\ F(t))(1 - \operatorname{sign}(\dot{F}) f g(\lambda)) \tag{2}$$

where $g(\lambda) = Z(\lambda) / (3Y(\lambda))$. Eq. (2) shows that, for the increasing load, friction causes reduction of the resulting SIF proportional to CoF value. To determine $g(\lambda)$, polynomial representation of $Y(\lambda)$ and numerical data for $Z(\lambda)$ were used. For $\lambda = 0.01 - 0.8$ the following simple formula

$$g(\lambda) = 0.157\lambda + 0.353 \tag{3}$$

approximates $g(\lambda)$ with accuracy of about 1%.

In the above analysis, the influence of friction on SIF values calculated for the same bending force was investigated. Now let us derive the similar formula for a displacement-controlled test.

Existence of friction, inevitably leads to dissipation of some energy during specimen deformation. Thus, to reach the same deflection of the specimen, more work should be done in the nonzero friction case than in the frictionless one. Due to this reason, for monotonically increasing load, the final bending force $F_f(t)$ reached for specimen deflection Δ for $f \neq 0$ must be higher than the similar force $F_0(t)$ for the frictionless case. Using virtual displacements principle, for monotonically increasing load, it is easy to show that if the deflection of the specimen additionally increases by infinitesimally small amount δ the following relation is satisfied

$$F_f(t)\delta = F_0(t)\delta + 2R_t(t)\delta_t \tag{4}$$

where δ_t is the tangential sliding displacement in the contact zone. Taking into account that $2R_t(t) = fF_f(t)$ and denoting $\alpha = \delta_t / \delta$, one can obtain

$$F_f(t) = F_0(t) / (1 - \alpha f) \tag{5}$$

In the similar way, for monotonically decreasing load, if displacement of the specimen decreases by infinitesimally small amount $-\delta$ from the initial value of Δ, the following relation can be obtained

$$F_f(t) = F_0(t) / (1 + \alpha f) \tag{6}$$

The value of dimensionless parameter α depends on λ and the relative specimen span S / W and changes within limits corresponding to $\lambda = 0$ (it is easy to prove that in this case $\alpha = W/S$ for pure bending of the simply supported crackless beam) and $\lambda = 1$ (similarly, $\alpha = 2W/S$ for bending of two rigid halves of the specimen connected by a point frictionless hinge at the loading point). Fitting of the results of finite element analysis (FEA) shows that for the standard relative beam span $S / W = 4$ and for the most important for practice range of $\lambda = 0.3$-0.7, values of α can be approximated by the following relation

$$\alpha(\lambda) = 0.215 + 0.284\lambda \tag{7}$$

with accuracy better than 1%. Finally, taking into account that $K_{\mathrm{I}}^{\mathrm{bend}}(t)$ depends linearly on load, substitution of Eqs. (3),(5)-(7) into Eq. (2) gives

$$K_I^{qs}(t) = \frac{1 - \mathrm{sign}(\dot{F})(0.353 + 0.157\lambda)f}{1 - \mathrm{sign}(\dot{F})(0.215 + 0.284\lambda)f} K_I^{bend}(t, F_0(t)) \tag{8}$$

Eq. (8) states that for growing load and $f \neq 0$, the fraction in the right-hand side of the equation is smaller than unity for all λ. It means that in the nonzero friction case, for monotonically growing load, SIF is always smaller than the similar value obtained for the same deflection of the specimen in frictionless case. The opposite is true for the decreasing load case.

2. Dynamic analysis – scope and initial assumptions

Quasi-static analysis presented above predicts that in the non-zero friction case for sufficiently long time after impact DSIF registered during the impact test is lower than the same value obtained in the frictionless case for the same specimen deflection. Additionally, both tup and anvil loads are higher than in the frictionless case. These conclusions, however, are based on the following assumptions:

- The specimen is always sliding with respect to the support
- Sliding direction does not change during a test
- Consequently, friction forces do not change their directions and absolute value of each force $|R_t(t)|$ is always equal to $fR_n(t)$.

Some of these assumptions are invalid, at least, for the preliminary stage of specimen deformation during an impact test when high oscillations of both tup and anvil forces are observed. During this stage, each friction force can either change its sign along with the sliding direction of the specimen with respect to the support or its absolute value can be lower than $|fR_n(t)|$ when the specimen is stick with the support. Due to these reasons, predictions of quasi-static theory and results of dynamic analysis could be different.

Dynamic calculations for the plane stress model of the impact specimen (Fig. 1) have been performed using commercial FE program ADINA 8.0.2 for the following sets of parameters: $L/W = 4.5(0.5)6.0$, $\lambda = 0.3(0.1)0.6$, $f = 0(0.1)0.8$, $r_t/W = 0.2$, $r_a/W = 0.25$. All calculations have been performed for:

- Poisson's ratio of the specimen material equal to 0.3
- Constant impact velocity $v = 7.5\times10^{-4}(E/\rho)^{1/2}$ (that corresponds to about 4 m/s for steels), where E and ρ are the Young's modulus and density of the specimen material, respectively
- Perfectly stiff striker and supports.

3. Results of dynamic analysis

Due to the space limit, only a small part of the numerical results obtained in this study will be presented below. More details will be published elsewhere. All results are presented in the non-dimensional form.

To check the accuracy and applicability of the formulae derived for the quasi-static case, the results of dynamic analysis performed for $f = 0$ and $f = 0.8$ for four different relative lengths of the specimen with $\lambda = 0.5$ are compared in Figs 2–5. In general, these results confirm predictions of the quasi-static analysis. For the same deflection, growth of CoF causes increasing of the mean values of both anvil and tup forces and decreasing of the mean DSIF value. Influence of friction on purely dynamic parameters of the load and DSIF such as amplitude and frequency of oscillations is ambiguous and depends on the specimen relative length. Friction increases the amplitude of load oscillation for relatively short specimens with $L/W = 4.5$, 5.0 (see Figs 2, 3) and reduces it for longer specimens with $L/W = 5.5$, 6.0 (see Figs 4, 5). For all but $L/W = 5.5$ cases, friction increases the amplitude of DSIF oscillations. Although there is a general tendency to increase the frequency of oscillation of forces and DSIF for all four specimens considered, the corresponding changes are small and unstable.

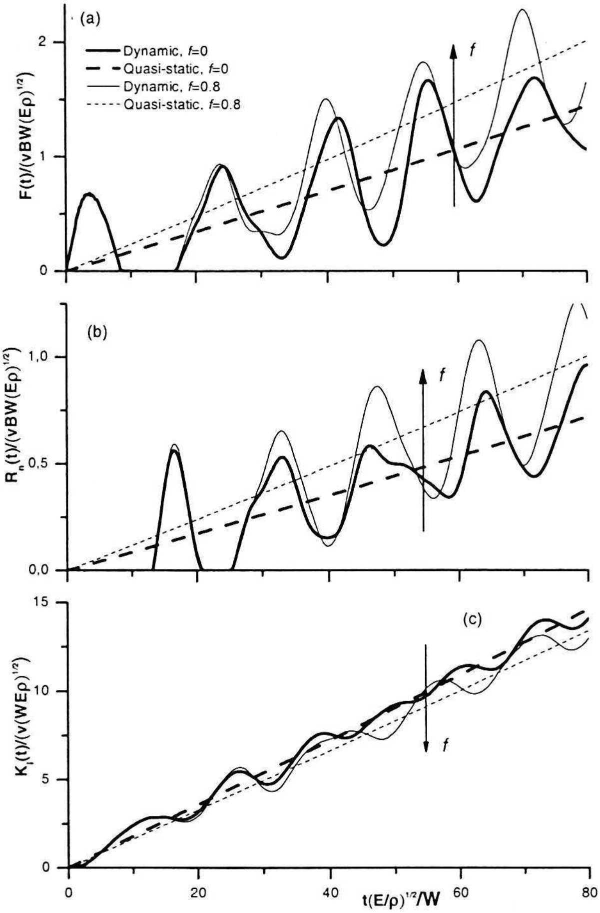

Fig. 2. Influence of friction on tup force (a), anvil force (b) and DSIF for L/W = 4.5

It is worth noting that in all cases for nonzero friction, the quasi-static forces are a bit higher than the mean values of the corresponding dynamic forces. Similarly, the quasi-static SIFs are a bit lower than the mean values of the corresponding DSIFs. It looks like the 'effective' CoF value for the dynamic analysis is slightly lower than for the quasi-static one. Fig. 6 provides the explanation of this phenomenon. This figure presents typical variations of the tangential or sliding velocity v_t in the specimen/support contact zone (Fig. 6a) together with the variation of the compressive friction force (Fig. 6b). The latter is compared with the 'slip-only' quasi-static friction force calculated as $fR_n(t)$. It is easy to see that the specimen's movement with respect to the supports is not continuous. Intervals of sliding are separated by the intervals of stick during which the friction force is lower than its quasi-static approximation. This causes the slight reduction of the influence of friction on the results of dynamic analysis when compared with the quasi-static one.

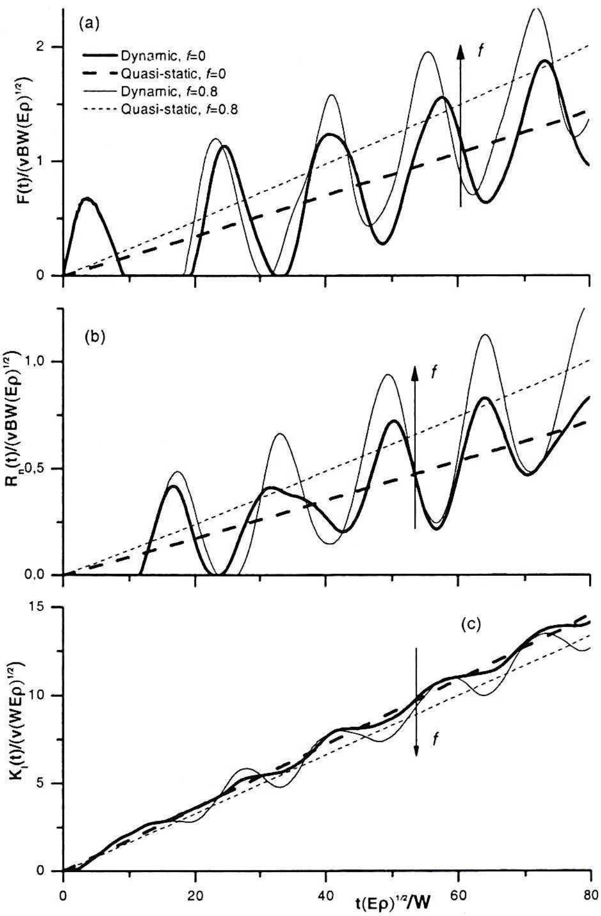

Fig. 3. Influence of friction on tup force (a), anvil force (b) and DSIF for L/W = 5

The presence of friction essentially affects both tup and anvil normal contact forces. Additional axial compression by friction forces makes specimen 'stiffer' and therefore reduces specimen 'bouncing' effect making shorter the time intervals during which the specimen has no contact with the tup or anvil. This phenomenon can be observed in the results presented in Fig. 7 for the striker force. Reducing of the 'bouncing' caused by friction is more noticeable for the relatively long specimens (Figs 7c, d) than for the shorter ones (Figs 7a, b).

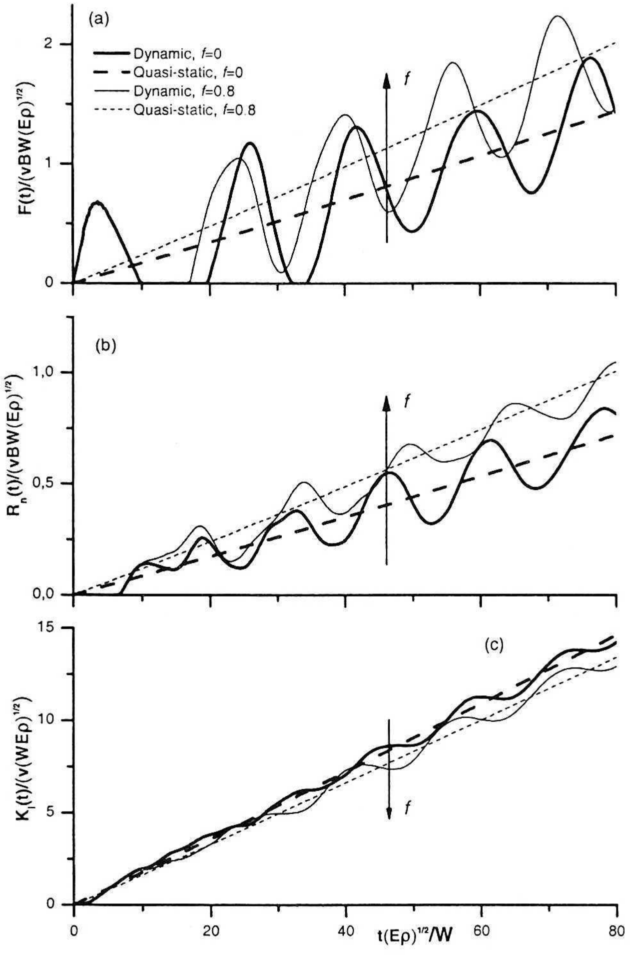

Fig. 4. Influence of friction on tup force (a), anvil force (b) and DSIF for L/W = 5.5

To predict roughly the changes in the amplitude of DSIF oscillations caused by friction, the following considerations may be taken into account. Typical DSIF-time diagram is wavy. Local 'peaks' of DSIF usually correspond to the periods of time when bending deformation of the specimen is high and therefore contact forces are low if any (Fig. 8). Thus, for such periods of time, the friction force is low or does not exist at all. Due to this reason, the friction caused reduction of the peak DSIF values is either low or does not exist.

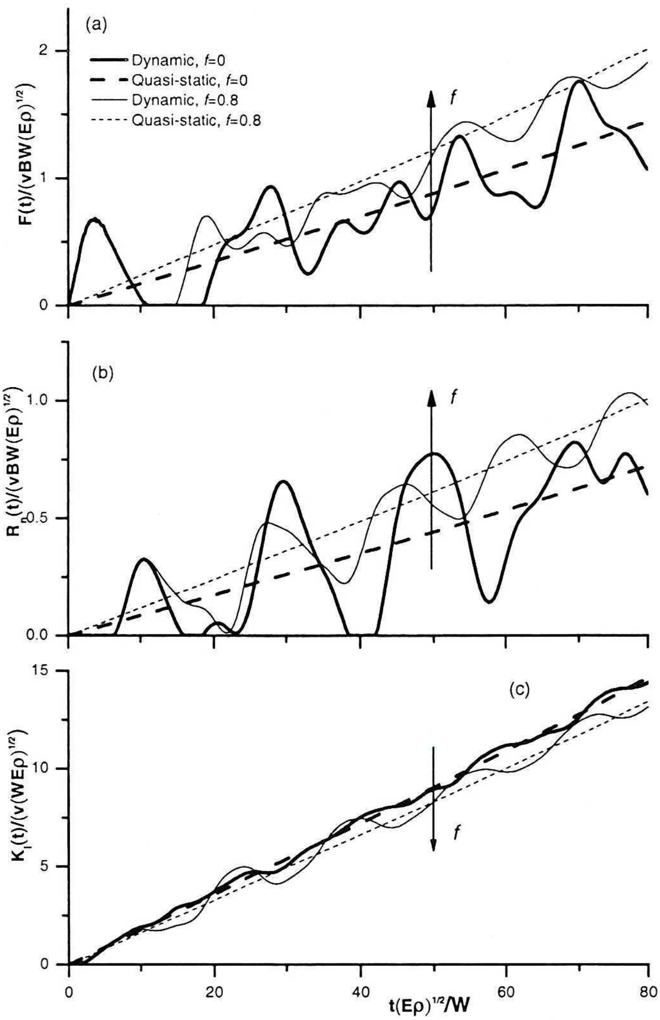

Fig. 5. Influence of friction on tup force (a), anvil force (b) and DSIF for L/W = 6

In contrast, 'valley' DSIF values correspond to low bending deformation of the specimen and high contact forces. Thus, the corresponding friction force is also high and causes essential reduction of DSIF. In total, friction should lead to the rise of the amplitude of DSIF oscillation mostly by reduction of the local DSIF minima.

Theoretical considerations presented above do not take into account consequences of possible sign changes of the friction force and finiteness of the time interval an elastic wave needs to pass a distance between the crack tip and a specimen/support contact point. Due to the latter reason, changes in friction force do not affect DSIF immediately and vice versa.

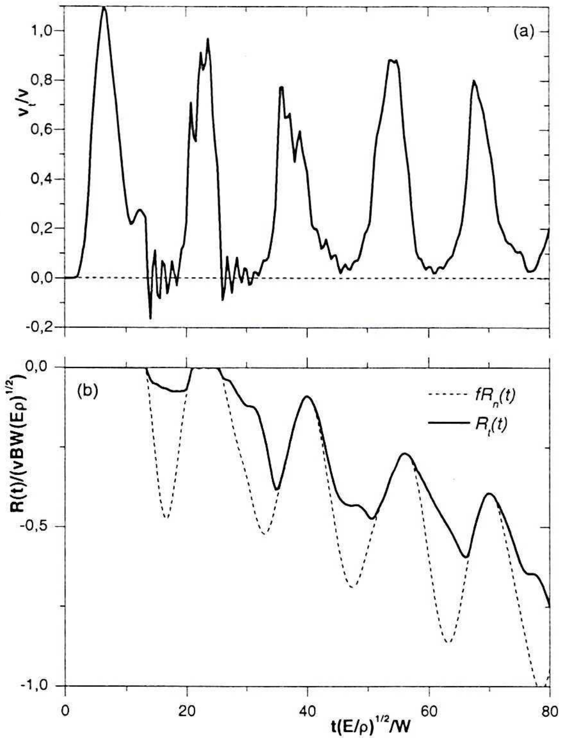

Fig. 6. Tangential velocities (a) and friction forces (b) in the specimen/support contact zone calculated for λ = 0.5, L/W = 4.5

To check the validity of the simplified analysis presented above, let us consider results obtained numerically. The amplitude of DSIF oscillations can be shown more clearly by considering a Dynamic Key Curve (DKC) that is the quotient of $K_I(t)$ and quasi-static SIF $K_I^{qs}(t)$ for the same deflection of similar massless specimen [3]. For the same configuration of the specimen, friction affects DSIF only after the one-point bending (1PB) stage (it means the time interval when deformation of the specimen is caused by $F(t)$ and inertia only) is finished. Thus, to calculate DKC properly, somebody needs to divide DSIF values by frictionless $K_I^{bend}(t)$ for 1PB stage of the test and by $K_I^{qs}(t)$, calculated using Eq. (8) for the rest part of the test.

Some of the results obtained by this procedure are presented in Fig. 9. For all but one relative length of the specimen considered, growth of CoF leads to the rise of the amplitude of DKC oscillation (see Fig. 7b for typical results). Only for $L/W = 5.5$ (Fig. 7a) small CoF values $f < 0.4$ cause DKC oscillation of the same or even smaller amplitude than in the frictionless case.

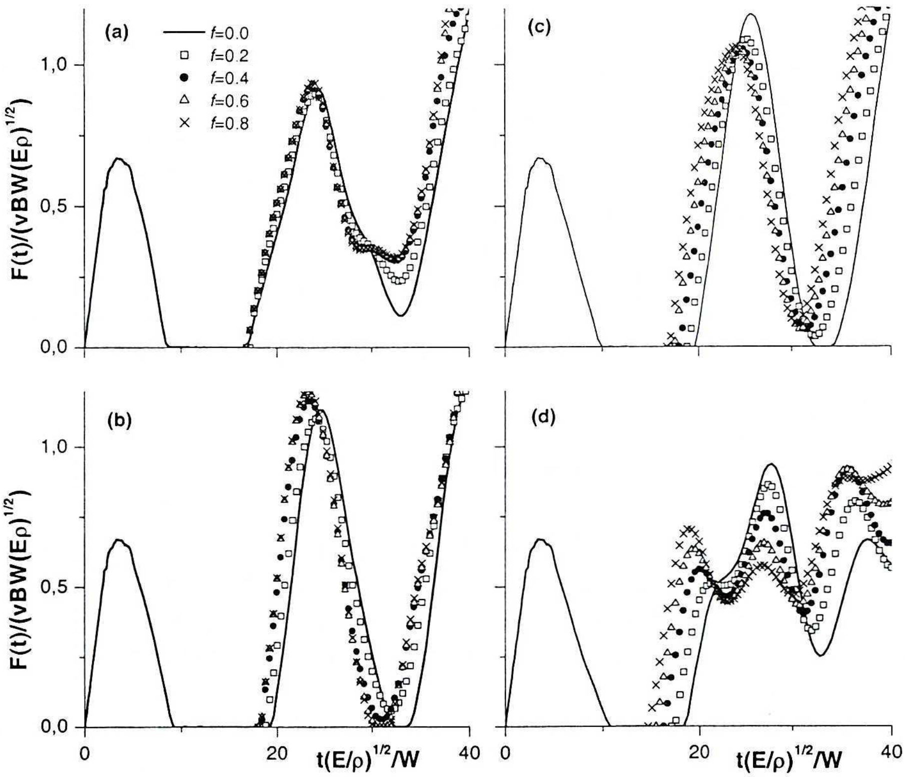

Fig. 7. Tup forces for λ = 0.5, L/W = 4.5 (a), L/W = 5 (b), L/W = 5.5 (c), L/W = 6 (d)

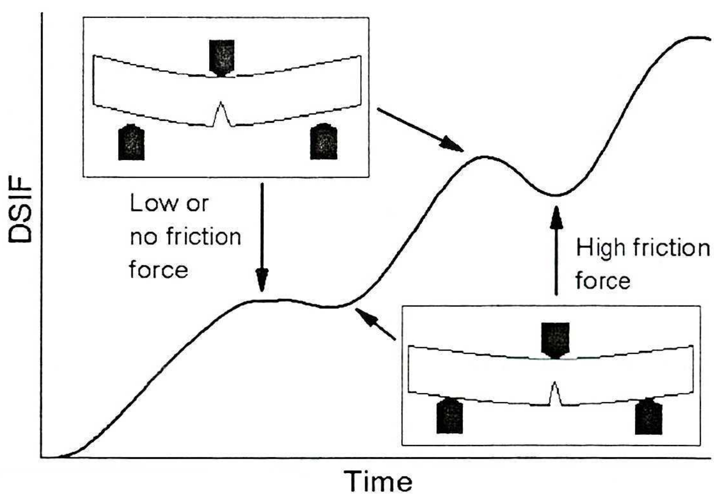

Fig. 8.Scheme of DSIF variation during an impact test

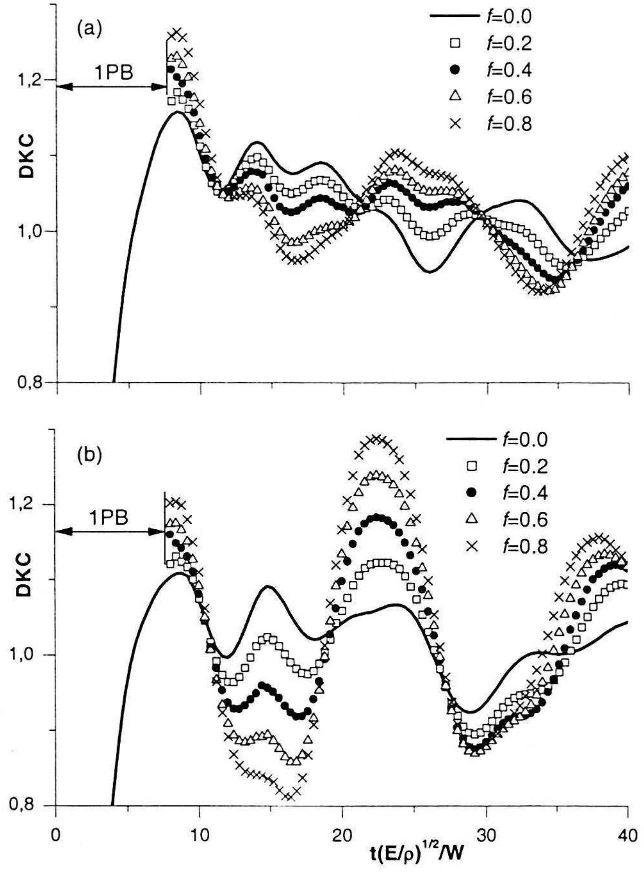

Fig. 9. Dynamic key curves vs time for $\lambda = 0.5$, $L/W = 5.5$ (a), $L/W = 6$ (b)

4. Conclusions

1. Friction between the specimen and the supports increases contact forces and decreases DSIF during the impact fracture test and should be taken into account especially for high CoF values.
2. Contrary to the quasi-static case, the relative movements of the specimen in the specimen/support contact zone are quite complex and include temporal stick conditions. Due to this reason friction force is not always equal to the normal contact force multiplied by sliding coefficient of friction.
3. In general, friction causes increasing of the amplitude of DSIF oscillation.

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Wpływ tarcia na wynik próby udarowej

Streszczenie

Przeprowadzono numeryczną analizę wpływu tarcia pomiędzy próbką a podporami w czasie próby udarowej na siły kontaktowe oraz dynamiczny współczynnik intensywności naprężeń (DWIN). Pokazano, że tarcie prowadzi do wzrostu średnich wartości sił mierzonych na bijaku i podporach młota. Dodatkowo, w większości przypadków tarcie powoduje wzrost amplitudy oscylacji DWIN i wskutek tego utrudnia interpretację wyników próby. Zaproponowane zostali proste wzory do uwzględnienia spowodowanego tarciem spadku średniej wartości DWIN.