# The Young's Modulus (E) and Fracture Toughness ($J_{IC}$) of MMCs Reinforced with $SiC_p$

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## ABSTRACT

The results of examining the crack resistance for magnesium matrix composites containing various amounts (5, 10, 20, 30 wt %) of silicon carbide particles were presented. For the determination of Young's modulus and fracture toughness, as measured by the integral $J_{IC}$, a specimen flexibility measurement method was used. The investigated composites showed that the modulus E grows proportionally to the weight fraction of SiC particles. The inversely proportional dependence between the $J_{IC}$ integral and the fraction of SiC particles contained in the MgAl5 matrix was also determined. In addition, the correlation between values predicted by a theoretical model and measured experimentally was discussed.

## 1. INTRODUCTION

The motive for making a composite is create materials with a profile of properties not offered by any monolithic materials. However, the dependencies determined from experimental investigations have not been reflected yet by a complete theoretical model describing the behaviour of these materials /1-7/. Most of the presently applied models relate composite properties to only two factors: matrix properties and reinforcement properties. The modulus of a composite is bracketed by the well known bounds /1,2/. The upper bound is found by postulating that, on loading, the two components suffer the same strain, the stress is then the volume-average of the local stresses and the composite modulus follows a "Rule of Mixture":

$$E_C = f \cdot E_R + (1-f) \cdot E_M \quad (1)$$

where $E_C$, $E_M$, $E_R$ - Young's modulus for the composite, the matrix and reinforcement, respectively, $f$ - volume fraction of reinforcement phase.

The lower bound is obtained by postulating instead that the two components carry the same stress and the strain is the volume-average of the local strains. The composite modulus is then describe as a "Reuss model":

$$E_C = \frac{E_M \cdot E_R}{f \cdot E_M + (1-f) \cdot E_R} \quad (2)$$

While considering metal composites reinforced with ceramic particles, which are frequently obtained by casting, one cannot apply models developed for fibre composites to search for correlations, especially the ones involving mechanical properties. The relationships derived on basis of the additivity laws are not valid here, either for the assumption of iso-stress or iso-strain conditions. The non-uniform distribution of stress and strain during loading composite materials means that the simple equal stress model is inadequate. The most successful of various empirical and semi-empirical expressions is that of Halpin and Tsai /2/. This is not based on rigorous elasticity theory, but broadly takes account of enhanced fiber load bearing, relative to the equal stress assumption. This model has been adopted from Maxwell's relationship between a parameter (a property) and the volume fraction, properties of components, and their interaction, in the form /8/:

$$y_C = y_O \cdot \left[ \frac{y_P + 2 \cdot y_M + 2 \cdot f(y_P - y_M)}{y_P + 2 \cdot y_M - f \cdot (y_P - y_M)} \right] \quad (3)$$

where $y$ means of calculates property.

Halpin-Tsai's expression for modulus is /2/:

$$E_C = \frac{E_M (1 + 2 \cdot \xi \cdot \eta \cdot f)}{1 - \eta \cdot f} , \quad (4)$$

where:

$$\eta = \frac{(E_R / E_M) - 1}{(E_R / E_M) + 2 \cdot \xi} , \quad (5)$$

The value of $\xi$ may be taken as an adjustable parameter, but its magnitude is generally of the order of unity.

Moll and Kainer /9/ have considered the relationship between composite properties and the shape of introduced particles, adopting Halpin-Tsai's model to determine the Young's modulus in composites. Because the results of their calculations differed from experimental data by about 30%, the authors suggested that the model is suitable for composites reinforced with particles exhibiting low shape factor values and being free of structural defects.

This work presents results of experimental determining of Young's modulus ($E$) and fracture toughness, as measured by the critical integral $J_{IC}$, of the magnesium matrix composites reinforced with SiC particles. For comparison purposes, the identical examinations have also been performed on the unreinforced matrix alloy.

## 2. MATERIALS AND EXPERIMENTAL PROCEDURE

### 2.1. Investigated material

The magnesium matrix alloy containing 5 wt. % of Al was prepared and various amounts of SiC particles: 5, 10, 20, 30 wt. % were used as the reinforcing phase. Composite samples were obtained by means of a simple and non-expensive casting method involving mechanical mixing of liquid metal, the introduction of particles under a protective argon atmosphere, and subsequent casting into metal moulds /10/. Typical microstructure of the MgAl5 matrix alloy composites containing 30 wt. % of silicon carbide particles is shown in Fig. 1.

It should be noted that investigated composites showed a uniform arrangement of the SiC particles within the matrix and a very strong bond between the components, as described in /10/. Fig. 2 shows a TEM image of the interface between an SiC particle and

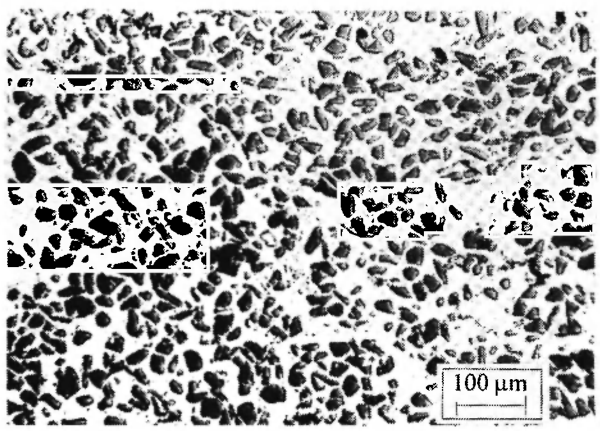



**Fig. 1:** Microstructure of the MgAl5-matrix composite reinforced with 30 wt % of SiC particles.

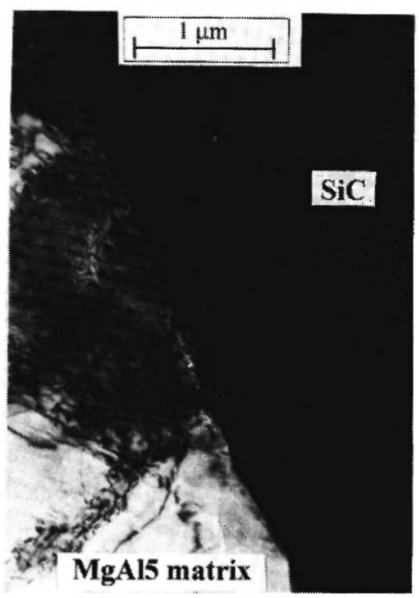



**Fig. 2:** Electron micrograph (TEM) of the interface between the SiC particles and the magnesium matrix

the MgAl5 matrix in the investigated composite, which confirms the adhesive character of the bonds between the matrix and silicon carbide particles.

## 2.2. Young's modulus and $J_{IC}$ integral examination

The fracture toughness tests were carried out by means of the three-point bending of standard specimens (12 × 26 × 144 mm) provided with a 12 mm deep notch. This was done on an MTS-810 servo-hydraulic testing machine. Signals indicating bending force (*P*), deflection (*f*), and crack mouth opening (*v*) coming from strain gauges were collected directly by two X-Y recorders. This permitted two types of graphs to be obtained, employing the *P÷f(d)* and the *P=f(v)* systems. The performed tests included experimental determination of (i) Young's modulus (*E*), and (ii) fracture toughness, as measured by the $J_{IC}$ integral. A specimen flexibility method, involving repeated loading and unloading of a specimen during its deformation period, was used for the determination of these quantities.

The specimen flexibility, $C_k$, in every successive loading cycle *k*, was determined from the relationship:

$$C_k = \Delta v_k / \Delta P_k , \tag{6}$$

where: $\Delta P$ and $\Delta v$ designate, respectively, the force and the variation of crack mouth opening as a function of displacement changes (according to Fig. 3a).

Since the flexibility is related to the relative crack length, *a*, by the function:

$$\left(a/W\right)_k = f(C)_k , \tag{7}$$

then the successive calculations as done in accordance with the standard were to determine the increments in the crack in the locations of consecutive loads using the following polynomial:

$$a_k/W = 0.999748 - 3.9504\mu_k + 2.9821\mu_k^2 - 3.21408\mu_k^3 + 51.51564\mu_k^4 - 113.031\mu_k^5 , \tag{8}$$

where the function $\mu_k$ is described by the equation:

$$\mu_k = \frac{1}{\left[\left(4\frac{W}{S}\right)BEC_k\right]^{1/2} + 1} , \tag{9}$$

in which: *W* – is the specimen height, *B* – specimen thickness, *S* – distance between the bending rolls, and *E* – Young's modulus.

Young's modulus, *E*, was calculated from the relationship:

$$E = \frac{6S}{BWC_0}\left(\frac{a_0}{W}\right)\left[0.76 - 2.28\left(\frac{a_0}{W}\right) + 3.87\left(\frac{a_0}{W}\right)^2 - 2.04\left(\frac{a_0}{W}\right)^3 + \frac{0.66}{(1-a_0/W)^2}\right] , \tag{10}$$

where $C_0$ is the average flexibility as determined from the first unloading (Fig. 3b).

The integral, $J_{IC}$, was evaluated following the procedure provided in the above mentioned standard. After the calculation of the final crack increment in the last point of the curve the results were corrected with the values measured on fractured specimens (the cracks were coloured). The measurements were taken in seven locations every 1/8 of the specimen thickness (Fig. 4).

Then, areas corresponding to the fracture energy, $E_k$, were planimetered on the *P=f(d)* curves for particular crack increments in successive specimen unloading steps. A schematic of the method for the determination of fracture energy is presented in the diagram (Fig. 5) obtained for MgAl5-SiC composites.

The value of the integral $J_k$ was calculated from the equation:

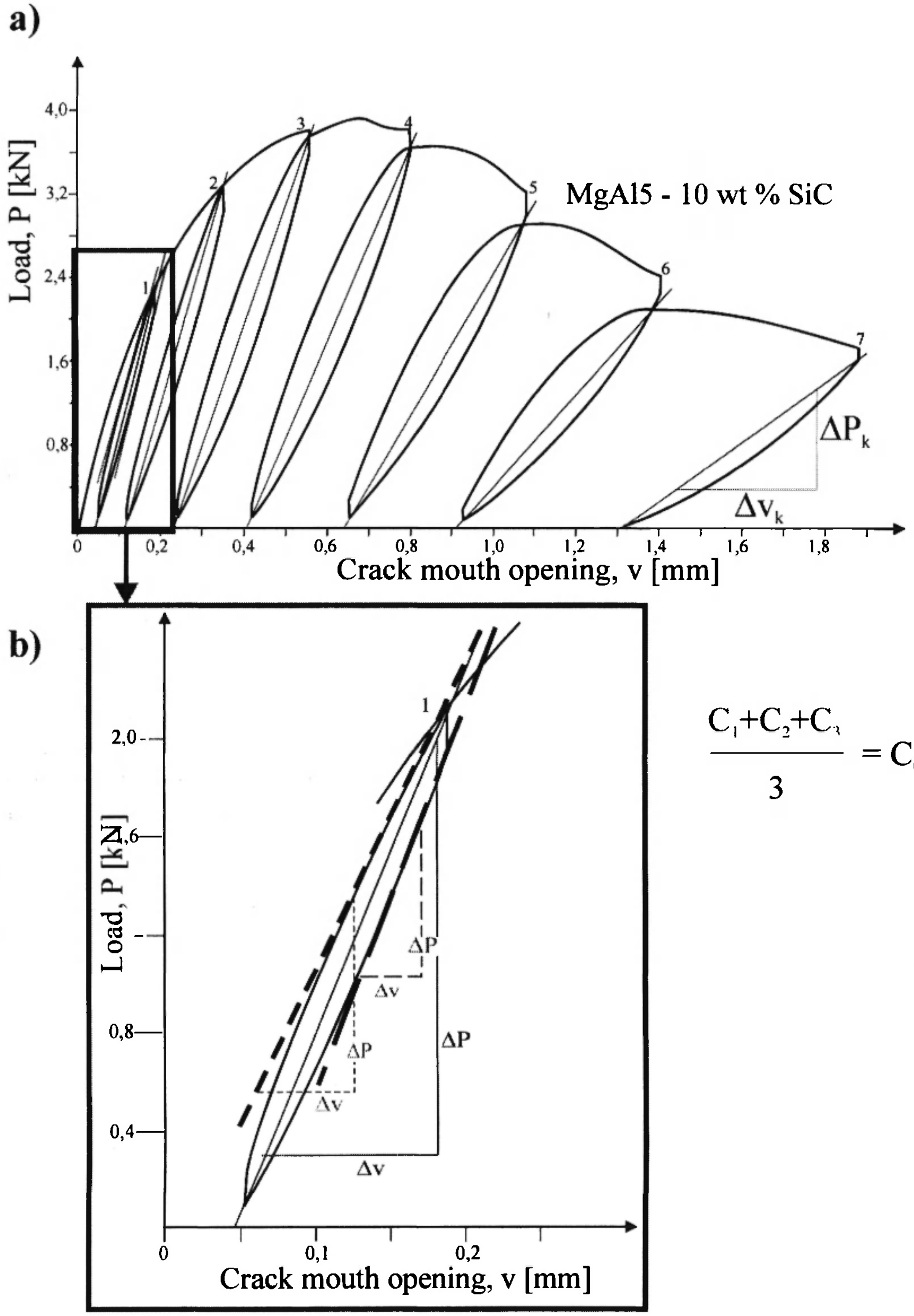
$$J_k = \frac{2E_k}{(W - a_k)B} , \tag{11}$$

while the blunting lines, *R*, were derived from the relationship:

$$R = \tfrac{1}{2}\left(R_{0,2} + R_m\right)\Delta a , \tag{12}$$

where: yield strength, $R_{0,2}$, and tensile strength, $R_m$, were determined from the standard tensile tests of the composites.

On the basis of the obtained $R_{0,2}$ and $R_m$ values, *J-R* curves were plotted, which enabled the searched critical




$$\frac{C_1+C_2+C_3}{3} = C_0$$

**Fig. 3:** Method of determining the flexibility $C_k$ and $C_0$.

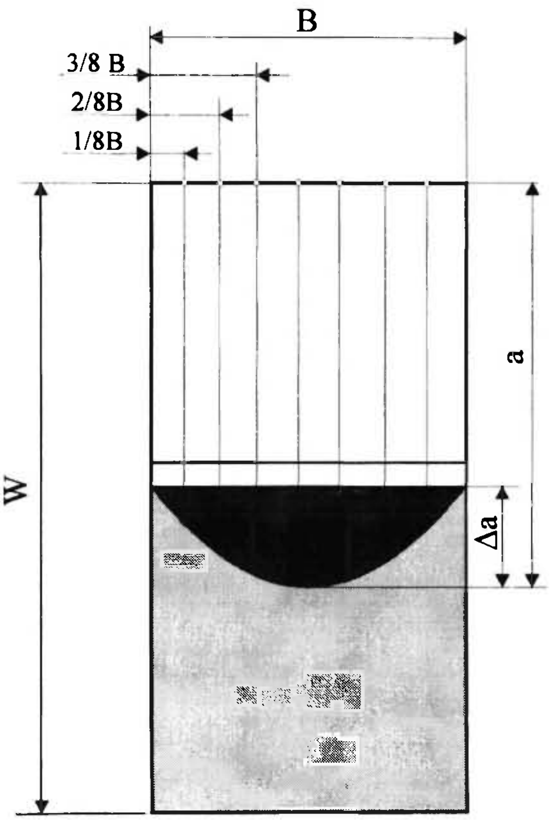



**Fig. 4:** Method of measuring the crack increments.

value of the integral $J_{IC}$ to be determined as the ordinate of the intersection of the $J_k=f(\Delta a)$ approximated function line and the blunting line, $R$ (Fig. 6).

## 3. RESULTS AND DISCUSSION

Based on the obtained examination results for Young's modulus, $E$, and the integral, $J_{IC}$, experimental curves were drawn, depicting the changes in the values of $E$ and $J_{IC}$ with increasing the weight fraction of SiC particles within the matrix of MgAl5-SiC composites.

The determined Young's modulus values for the investigated composites showed a directly proportional relationship between the modulus and the weight fraction of SiC particles (Table 1). The addition of 30 wt. % of silicon carbide particles caused a 42% increase in the value of $E$ modulus as compared to the non-reinforced matrix alloy. It should be noted that formation of the Mg alloy - SiC particle adhesive bonding contributed to proceeding cracking process of the composites mostly through silicon carbide particles This process is documented by scanning microphotographs taken for two mutually corresponding fracture surfaces (Fig.7a and b).

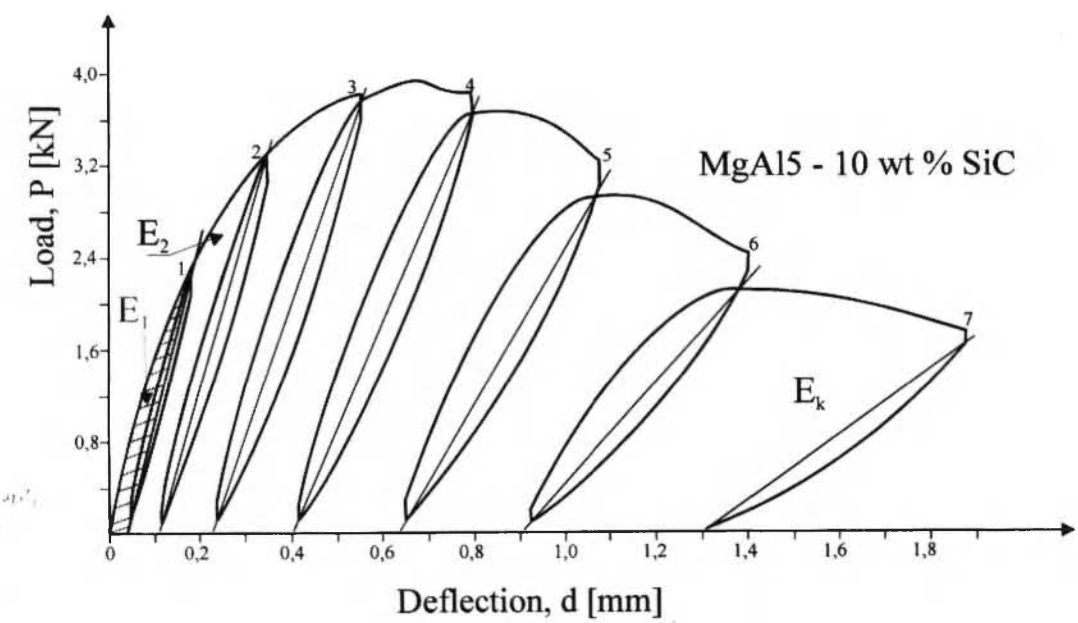



**Fig. 5:** Areas of integrating the fracture energies: $E_1$, $E_2$, , $E_k$ for successive unloading stages.

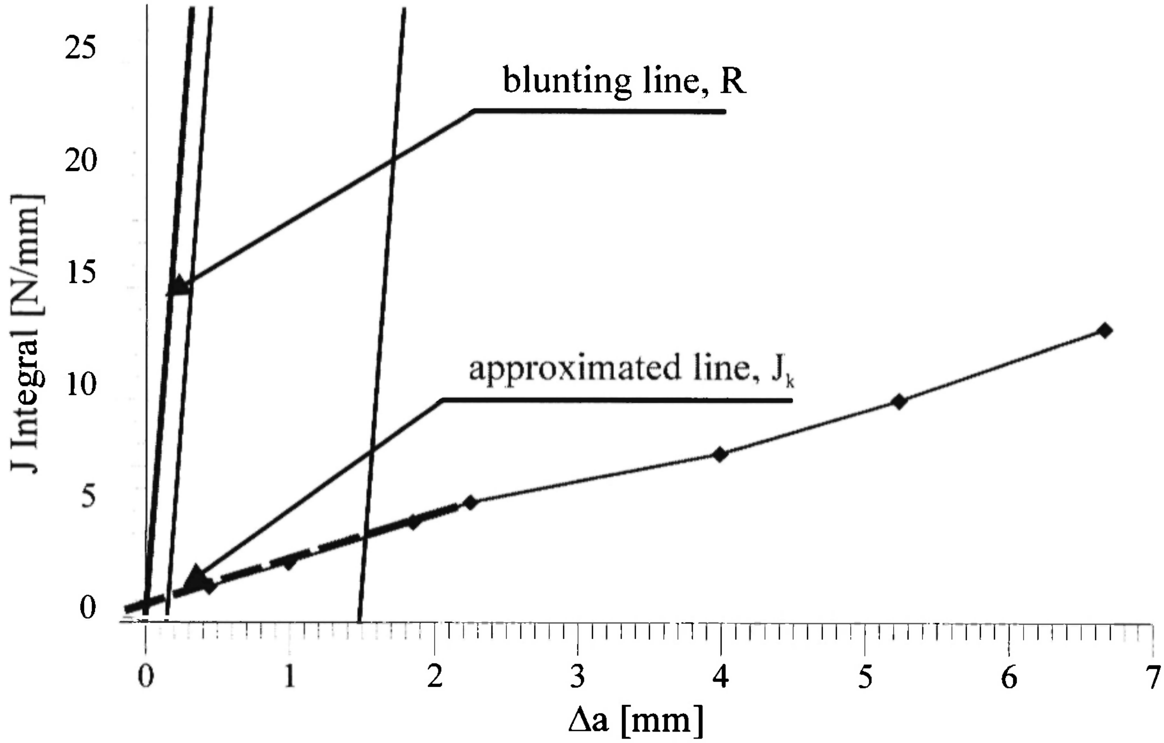



**Fig. 6:** Examples of blunting line, R and approximated line, $J_k$, as derived for the MgA15 – 10% SiC composites.

**Table 1**
The examined Young's modulus $E$ and integral $J_{IC}$ values of MgA15-$SiC_p$ composites.

| Investigated materials | Young's modulus, $E$ [GPa] | Integral $J_{IC}$ [N/mm] |
|---|---|---|
| MgA15 alloy | 37 | 2.1 |
| MgA15 - 10 wt % SiC | 43 | 1.1 |
| MgA15 - 20 wt % SiC | 52 | 0.59 |
| MgA15 - 30 wt % SiC | 64 | 0.48 |

In order to find the mathematical expression for Young's modulus of investigated composites reinforced with silicon carbide particles, Halpin and Tsai's model (eq. 4) was used. The shear lag model was adopted to show good cohesion between components to describe the $\xi$ parameter /2/. This model originally described the effect of loading an aligned short-fibre composite, which centres on the transfer of tensile stress from matrix to fibre by means of interfacial shear stresses.

The basis of analysis is shown schematically in Fig. 8. In this diagram, external loading is applied parallel to the particle diameter. The build-up of tensile stress in the particle $\sigma_p$ is determined from distribution of interfacial shear stress. The basic force balance acting on the particle is:

$$\pi \cdot r^2 \cdot \tau_i dx = -\pi \cdot r^2 d\sigma_p \qquad (13)$$

where $\tau_i$ is the shear stress at the particle/matrix interface, $r$ – the particle's radius, and $x$ – direction of the displacement according to axis acting of external loading.

The variation of the shear stress at the particle/matrix interface is derived by differentiating equation 13, neglecting the $r$ component. In this case the shear stresses at the particle/matrix interface, $\xi$ parameter, obtain a value equal to 1.

Fig. 9 presents experimental data as compared with theoretical values obtained from Eq. 4 for Young's

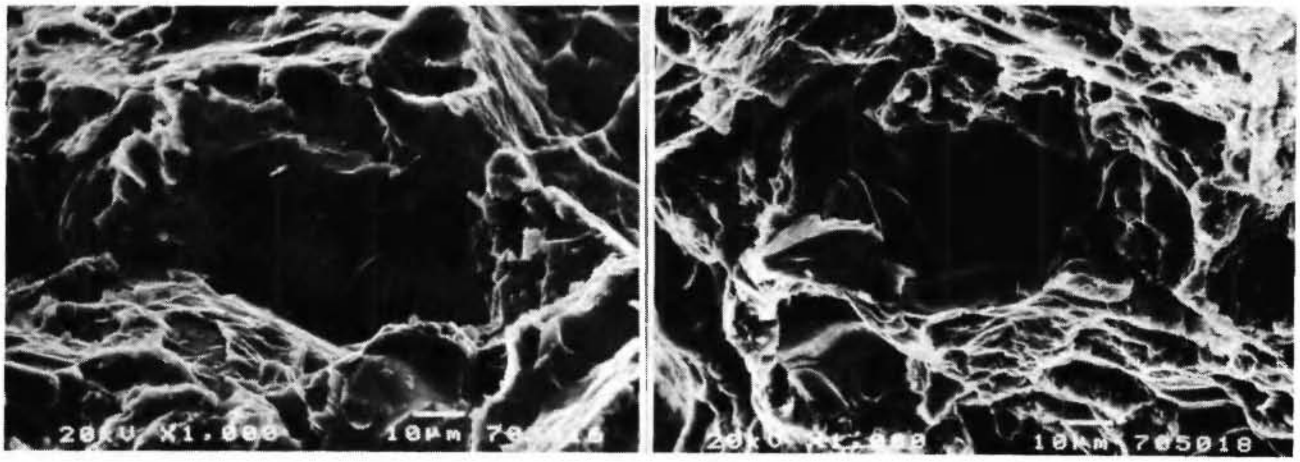



**Fig. 7:** SEM micrographs of the corresponding fracture surfaces of MgAl5-30wt%$SiC_p$ composites.

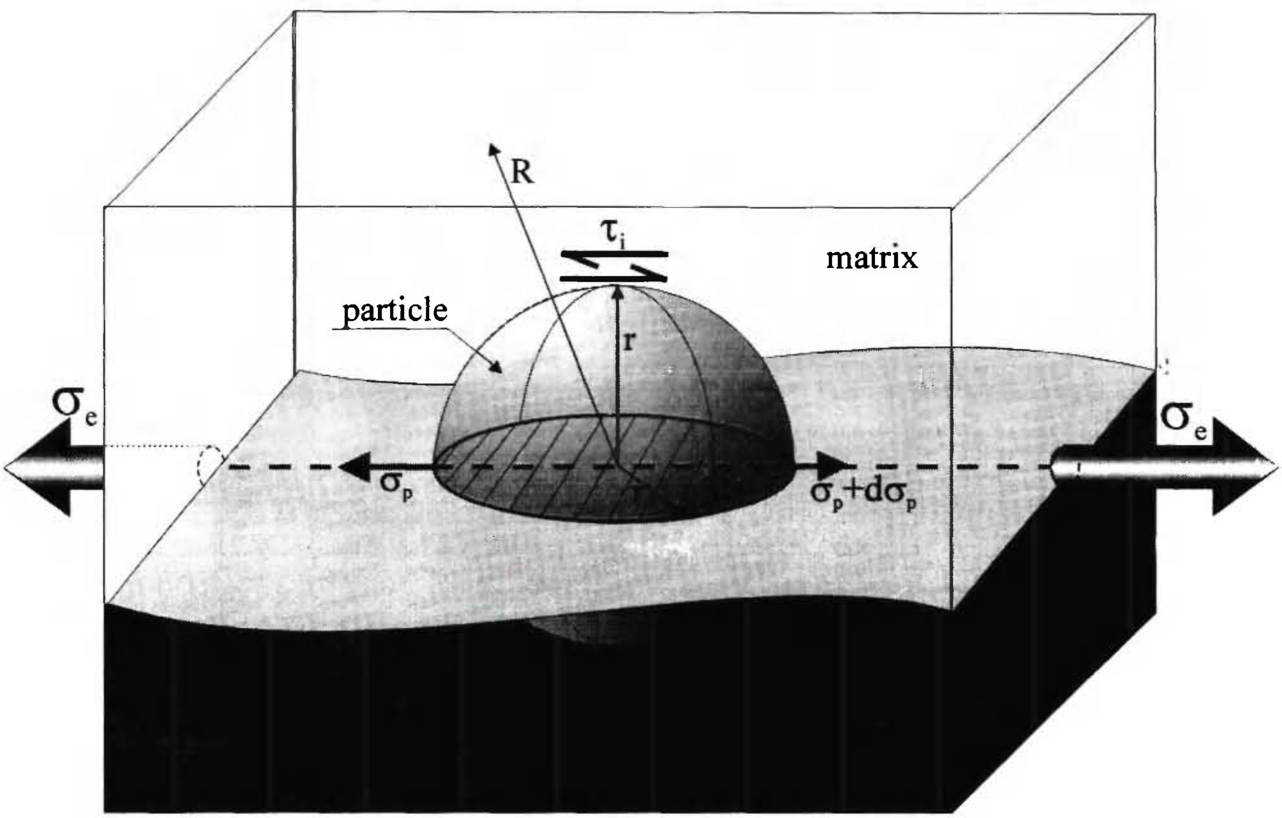



**Fig. 8:** Schematic illustration showing variation with radial location of the shear stress and strain in the matrix; the radius *R* represents far-field radial distance from particle axis.

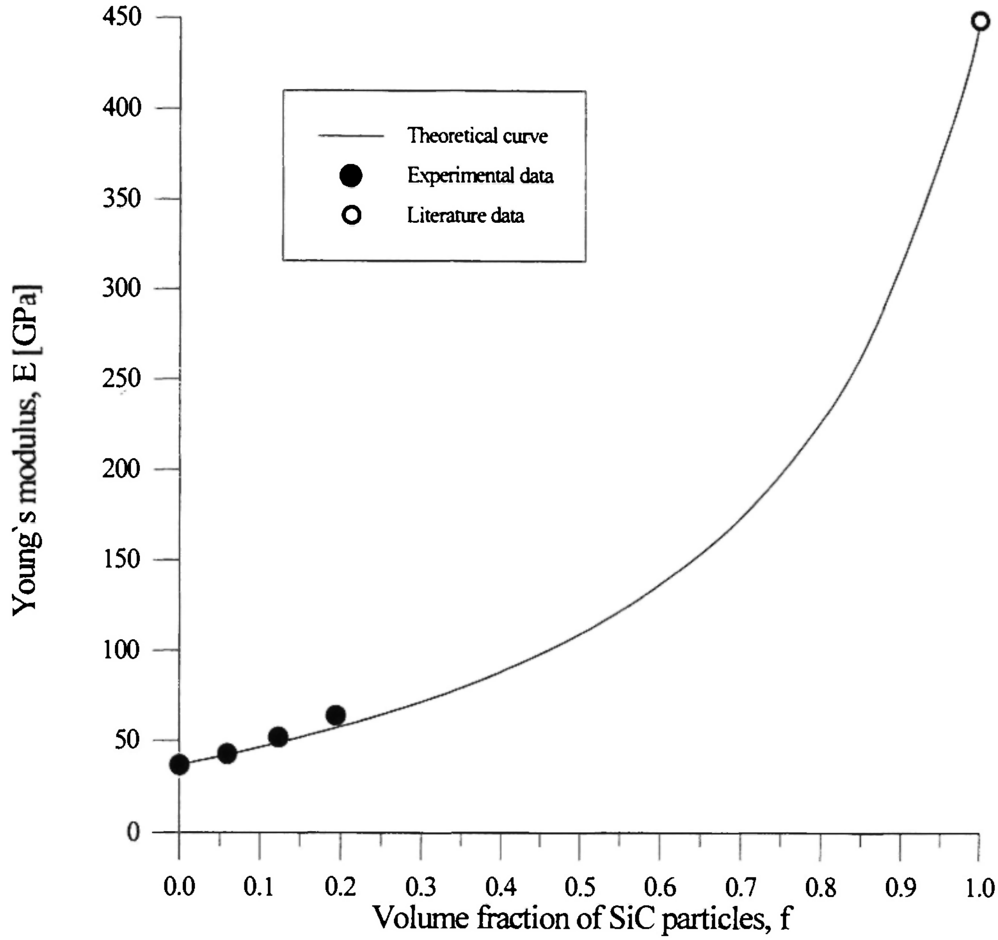



**Fig. 9:** Dependence of Young's modulus, *E*, on the SiC particle fraction in a composite (theoretical curves and experimental data)

modulus versus SiC volume fraction. This figure presents direct confirmation of the results of experiments performed for Mg/SiC composites and Halpin-Tsai expression.

The results of fracture toughness tests, carried out to determine the integral $J_{IC}$ of investigated composites, are presented in Table 1. Experimental data illustrates the inversely proportional relationship between fracture toughness and SiC particle fraction in the matrix.

For mathematical description of this relationship Halpin-Tsai expression has been used. In this case, however, the shear stress at the interfaces between the components could not be considered since the fracture process appears in composite materials. In equation (4) the $\xi$ parameter must be considered the equal of the reciprocal of particle diameter. Theoretical calculations of the values of $J_{IC}$ integral as a function of volume fraction of SiC particles have also shown good confirmation of obtained experimental data (Fig. 10).

## 4. CONCLUSIONS

The presented experimental procedure allowed for relatively accurate determination of the Young's modulus $E$ and the $J_{IC}$ integral for examined composites. It seems that other procedures of measuring the fracture toughness are not reliable for these materials. On the other hand, the presented procedure is quite arduous and demands for fixing numerous experimental curves, thus

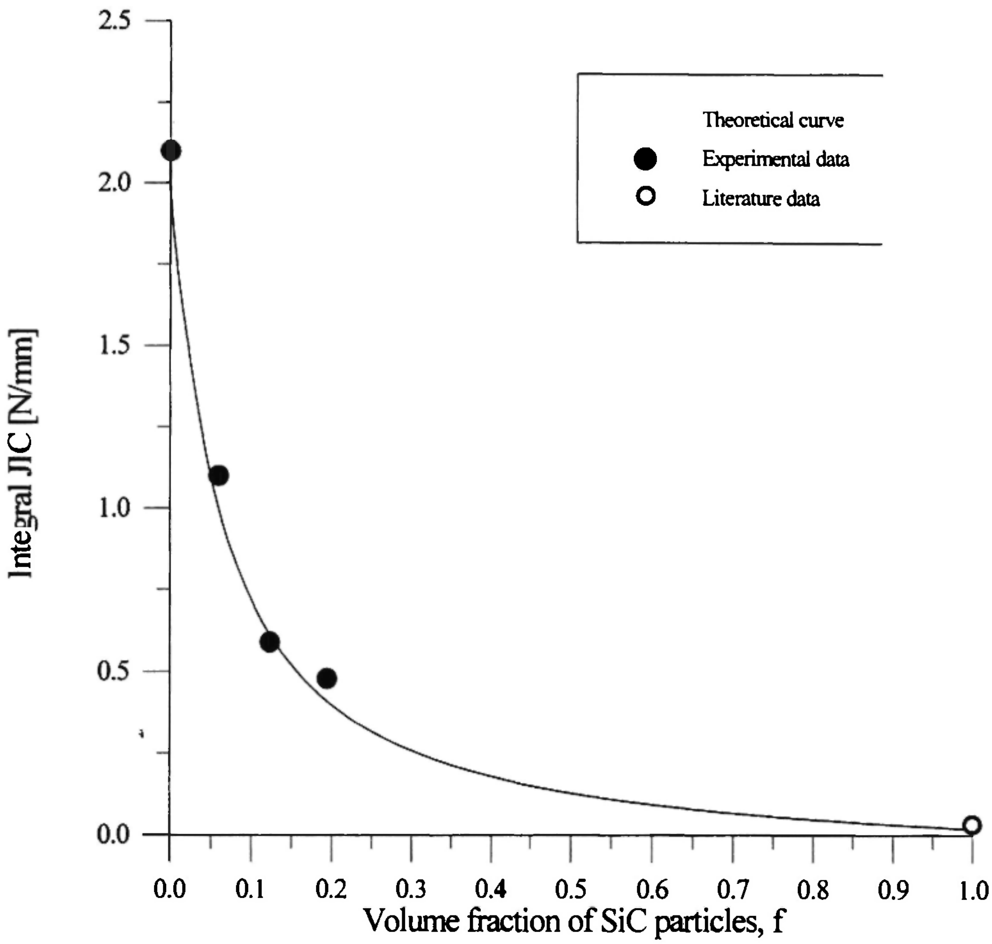



**Fig. 10:** Dependence of the integral $J_{IC}$ on the particle fraction for the MgAl5 – $SiC_p$ composites (theoretical curves and experimental data)

increasing the possible influence of human error.

Nevertheless the main factors responsible for the loss of the fracture toughness in composites are porosity, rigidity, and brittleness, the latter two of which increased due to the presence of ceramic particles. The possibility of improving the crack resistance is not very likely, considering the metal-particles system itself. The only possibility of improving the $J_{IC}$ integral would be through enhancement of the properties of the matrix alone.

After a series of analyses and experiments on composites reinforced with particles it seems that the most adequate model would be the one adopting Maxwell's relationship between a parameter (a property) and the volume fraction, properties of components, and their interaction. This function shown in a general form by Eq. 3 has found rather strong confirmation in the results of experiments performed for MgAl5 - $SiC_p$ composites.

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