Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 14
ISSUE 1-2
January-February
2006

Effect of morphology of eutectic silicon crystals on mechanical properties and cleavage fracture toughness of AlSi5Cu1 alloy

M. Wierzbińska*, J. Sieniawski
Rzeszów University of Technology, ul. W. Pola 2, 35-959 Rzeszów, Poland
* Corresponding author: E-mail address: mwierzb@prz.edu.pl

Received 15.11.2005; accepted in revised form 31.12.2005

Materials

ABSTRACT

Purpose: The purpose of this paper is presentation of the results that concerned the influence of morphology of eutectic silicon crystals on mechanical properties, especially on the cleavage fracture toughness of AlSi5Cu1 alloy.
Design/methodology/approach: Microscopic studies – optical microscope NIKON 300 and quantitative analysis of geometrical parameters of microstructure – image analysis program APHELION, tensile and fracture toughness tests – testing machine INSTRON 8810.
Findings: The sizes of silicon crystals and values of yield strength, tensile strength and plane strain fracture toughness have been determined. Relationships between mechanical properties and silicon crystals size were described using Hall-Petch equation. It was found that a decrease in silicon crystals causes an increasing in strength and in fracture toughness.
Practical implications: This paper is part of the previous author's investigations which results in modification of the casting technology of turboblower compressor impellers.
Originality/value: The microscopic observations indicated that alloy cracking begins with nucleation and growth of micro-cracks in the silicon crystals of large size, in orthogonal plane to tension direction. The hard and brittle silicon crystals are very strong barriers for slip in the stressed alloy.
Keywords: Aluminium alloys; Mechanical properties; Fracture mechanics; Plane strain fracture toughness; Metallography and quantitative metallography

1. Introduction

Mechanical properties of Al-Si alloys mainly result from their microstructure: morphologically diversified silicon precipitations are relatively hard and brittle particles held within in a softer, more ductile matrix material on the base of α(Al) solid solution [1-2]. Generally [3] it is possible to describe the relationship between the average strain in the alloy and relative volume of α(Al) and β(Si) phases using the following linear function:

$$\sigma = \sigma_\alpha V_V(\alpha) + \sigma_{Si} V_V(Si) \qquad (1)$$

where: σ_α, σ_{Si}-strains corresponding to the unit of phase volume.

However the fracture toughness, expressed as a plane strain fracture toughness K_{Ic}, depends on elastic and plastic properties of matrix and on the morphology and sizes of brittle phase particles [4-7]. These parameters, may significantly diversify the properties of the alloy with identical relative volume of silicon crystals $V_V(Si)$, are not taken into account in the equation (1). Influence of the morphology of the polycrystalline microstructure on the yield strength is defined by Hall-Petch equation [8]:

$$\sigma_{HP} = \sigma_o + k_m d^{-1/2} \qquad (2)$$

where:
σ_{HP} - the yield strength,
σ_o - total resistance of lattice against dislocation movement,

k_m - the hardening parameter, determining the effect of hardening connected with grain boundaries,
d - the average diameter of the grain.

According to Conrad [8] the strain value of σ_o may be divided into two components: I) σ_D - independent of the temperature but dependent on the type of structure. This component characterize the interaction between dislocations and precipitations and alloy additions; II) σ_P- dependent on the temperature and connected with Peierls-Nabarro strains. Assuming these the following equation (2) can be written:

$$\sigma_p = \sigma_P + \sigma_D + k_m d^{-1/2} \quad (3)$$

where:
σ_P – Peierls' strains (< 1.0 nm), short range of the interaction,
σ_D – stress fields of dislocations (10.0-100.0 nm), average range of the interaction,
$k_m d^{-1/2}$ - microstructural effect (> 103 nm), long range of the interaction.

The influence of the degree of refinement of microstructure on the yield strength has a long range interaction character [8-13]. Many recent researches have shown, that in the case of materials with dendritic structure, the measure of microstructural effect in Hall-Petch equation are primary (λ_1) or secondary (λ_2) dendrite arms spacing [14-17]. However according another analysis [18-19] conducted on AlSi5Cu1 alloy, both yield strength and tensile strength of tested alloy depend, to the highest degree, on sizes of eutectic silicon crystals. Results of plane strain fracture K_{Ic} examinations also confirm the strong effect of eutectic silicon crystals sizes on fracture toughness of AlSi5Cu1 alloy. Therefore this work, which is continuation of authors' previous research [18,20], has been solely concentrated on the influence of eutectic silicon crystals on mechanical properties of the alloy.

2. The material and experimental procedure

The investigation was conducted on four variations (four different microstructures) of hypoeutectic AlSi5Cu1 alloy with composition as given in the Table 1.

Table 1.
Chemical composition of AlSi5Cu1 alloy

Chemical element, %								
Si	Cu	Mg	Mn	Fe	Ti	Cr	Zn	Sn
5.02	1.03	0.50	0.01	0.14	0.16	<0.05	<0.01	<0.004

3. Results and discussion

Values of relative volume of eutectic silicon crystals $V_{V(Si)}$ are shown in table 2.

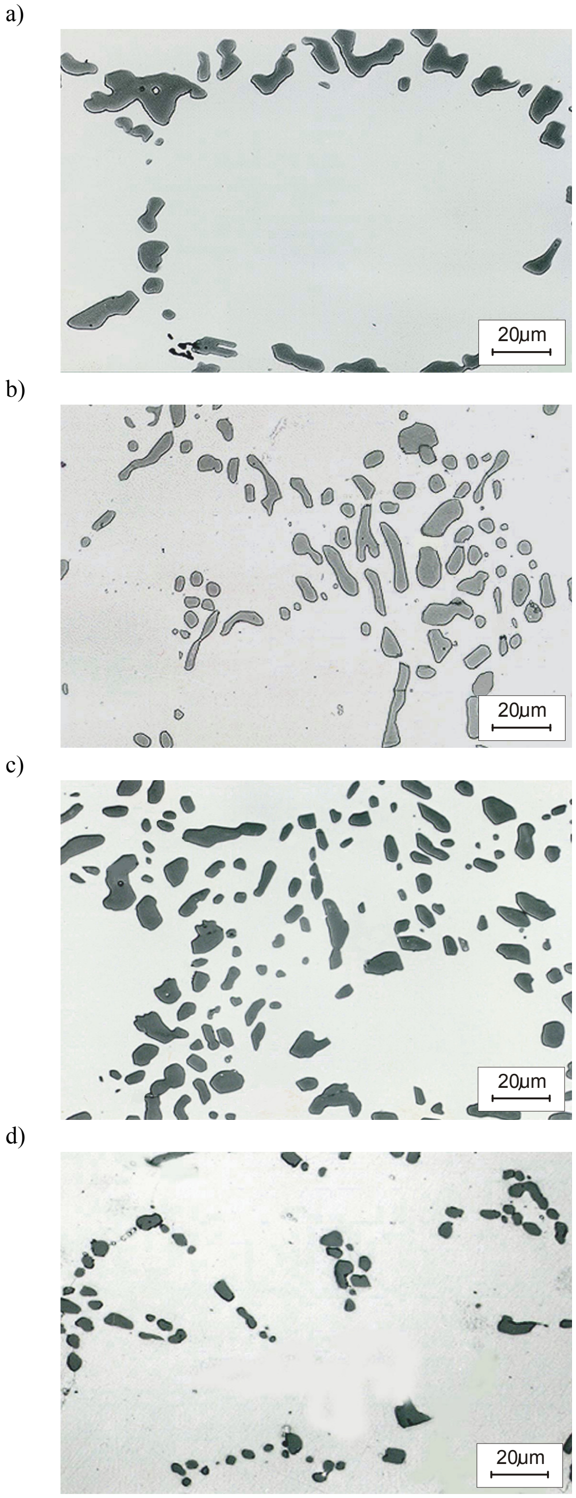

Fig. 1. Microstructure of AlSi5Cu1 alloy as a function of cooling rate during solidification: a) microstructure A (0.5 Ks^{-1}), b) microstructure B (7.5 Ks^{-1}), c) microstructure C (19 Ks^{-1}), c) microstructure D (30 Ks^{-1})

Table 2.
Relative volume of eutectic silicon crystals depending on the microstructure A, B, C and D of the AlSi5Cu1 alloy

Relative volume	Microstructure variety			
	A	B	C	D
V_V	4,90 (2,07; 42)	4,95 (1,93; 40)	4,95 (1,91; 38)	4,80 (0,95; 20)
V_V(F)	3,30 (1,28; 39)	3,01 (1,14; 38)	2,50 (0,91; 36)	2,09 (0,51; 24)

Standard deviations s and coefficient of variation W_z percentage are listed in parentheses

Results of quantitative analysis of geometrical parameters of eutectic silicon crystals are given in Table 3. These values are the arithmetic mean determined from large quantity of data - 214 thousand for A alloy (in it 29.6 thousand of fractured crystals), 86 thousand for B alloy (28.7 thousand of fractured crystals), 142.8 thousand for C alloy (25.7 thousand of fractured crystals) and 211.6 thousand for D alloy (59.2 thousand of fractured crystals).

Table 3.
Geometrical parameters characterizing sizes of eutectic silicon crystals for A, B, C and D variations of the microstructure AlSi5Cu1 alloy

Geometrical parameters	Microstructure variety			
	A	B	C	D
$\overline{d}$, μm	4,25 (1,58; 37)	4,95 (1,93; 40)	4,95 (1,91; 38)	4,80 (0,95; 20)
$\overline{d}$ (F), μm	6,03 (1,01; 17)	3,01 (1,14; 38)	2,50 (0,91; 36)	2,09 (0,51; 24)

Standard deviations s and coefficient of variation W_z percentage are listed in parentheses

The values of angle between the direction of cracking and direction of applied load in tensile tests are shown in the form of the histogram (Fig. 2).

The mechanical properties are shown in Table 4.

Mechanical properties of aluminium-silicon alloys are strictly connected with presence of the eutectic silicon crystals, particularly with their relative volume, distribution shape and sizes. Relative volume of eutectic silicon crystals is primarily resulting from the chemical composition of the alloy. However, since each of four varieties of the alloy microstructure were prepared from the same melt, the values of relative volume of silicon crystals in all these cases are practically identical (see Tab. 2). Analysis of variance of the relative volume's value – F test according to Snedecor [21] allowed to estimate the degree of distribution of eutectic silicon crystals in A, B, C and D alloys.

It was found, that for the A, B and C microstructures, the values of variance were nearly identical to each other. It follows that there were no significant differences between the distribution of eutectic silicon crystals in A, B and C microstructures (values of coefficient of variation ≈40%). However, difference occurred in the D type of microstructure, which was simultaneously characterized by the highest uniformity of distribution of eutectic silicon crystals (coefficient of variation ≈ 20%).

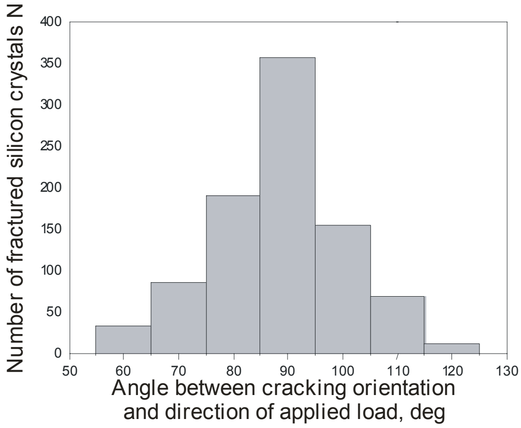

Fig. 2. Distribution of the value of angle between the cracking orientation in silicon crystals and direction of applied load in static tensile test

Table 4.
Results of tensile properties and plane strain fracture toughness of AlSi5Cu1 alloy related to microstructure variety

Microstructure variety	Mechanical properties		
	R_{02}, MPa	R_m, MPa	K_{Ic}, MPa $m^{-1/2}$
A	228 (17,2; 7)	299 (15,1; 5)	22,7 (0,6; 2,8)
B	239 (17,4; 7)	324 (10,6; 3)	24,0 (0,4; 1,6)
C	242 (18,7; 8)	330 (18; 5)	24,4 (0,4; 1,6)
D	250 (17,1; 7)	346 (24; 7)	26,5 (0,4; 1,4)

Standard deviations and coefficient of variation percentage are listed in parentheses

The analysis of the influence of eutectic silicon crystals sizes $\overline{d}$ on mechanical properties – yield strength $R_{0,2}$ and, for comparison purpose only, on ultimate tensile strength R_m, was performed with using Hall-Petch equation (Fig. 3 and 4). The following relationship were received:

$$\overline{R}_{0,2} = 59{,}08 + 356 \cdot \overline{d}^{\,-1/2}; \quad r = 0{,}977 \qquad (4)$$

$$\overline{R}_{m} = -\,58{,}92 + 756 \cdot \overline{d}^{\,-1/2}; \quad r = 0{,}968 \qquad (5)$$

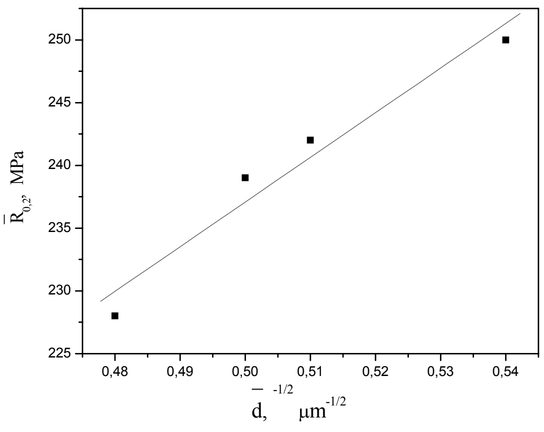

Fig. 3. Yield strength $R_{0.2}$ of AlSi5Cu1 alloy as a function of eutectic silicon crystals size *d*

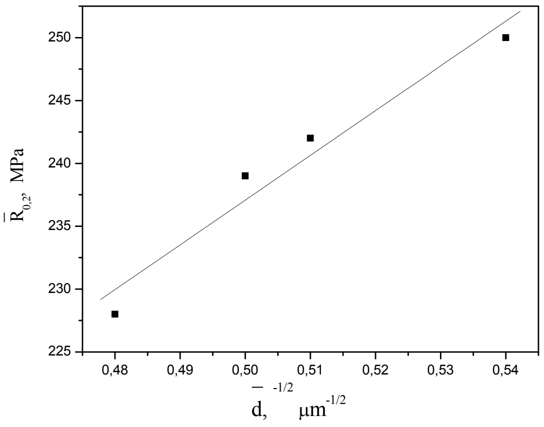

Fig. 4. Tensile strength R_m of AlSi5Cu1 alloy as a function of eutectic silicon crystals size *d*

It is shown that size of eutectic silicon crystals also has considerable influence on the fracture toughness of AlSi5Cu1 alloy. The linear relationship between K_{Ic} and *d* (Fig. 5) may be represented by the following formula:

$$\overline{K}_{Ic} = -7{,}52 + 62{,}89\cdot \overline{d}^{\,-1/2}; \quad r = 0{,}998 \qquad (6)$$

The values of regression coefficients in the equations 4-6 testify that eutectic silicon crystals are very strong barrier for slip. It was confirmed by the results of microstructural observations on the polished surfaces of samples after slow tension (1 mm min^{-1}), as illustrated in Figs. 6. The arrows in these figures show the direction of tensile deformation. Eutectic silicon crystals are cracking when shear stress, expressed with Smith and Barnby relation [22] reaches a critical value.:

$$K_{Ic} = \sigma_0 \sqrt{25x_0} \qquad (7)$$

where: σ_0 – stress equivalent to the yield point, x_0 – minimal length of crack determining its expansion

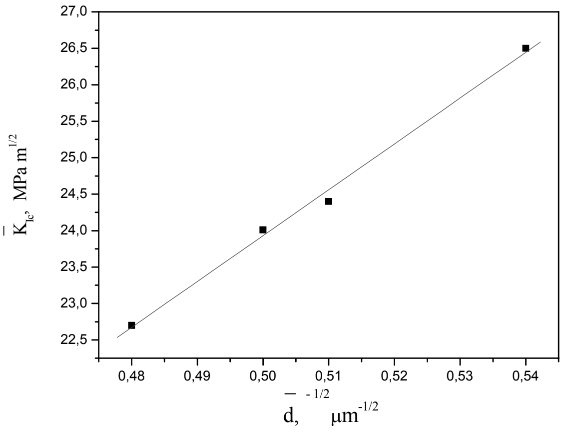

Fig. 5. Plane strain fracture toughness $\overline{K}_{Ic}$ of AlSi5Cu1 alloy as a function of eutectic silicon crystals size *d*

Results of examinations indicated (see Fig. 6 a-d) that for the AlSi5Cu1 alloy this value is exceeded at the lower strain than the tensile strength value. The direction of cracking of eutectic silicon crystals is the most often perpendicular to the tension direction (Fig. 6 a-c). It confirms that the direction of applied load play dominant role in cracking of eutectic silicon crystals.

Relative volume of fractured eutectic silicon crystals, due to large quantity of tested particles, successfully reflects the cracking probability of the alloy that linearly increase with increasing of eutectic silicon crystals sizes (Fig.7), according to following formula:

$$\overline{V_V}(F) = -3{,}52 + 1{,}61\cdot \overline{d}\ ; \ r = 0{,}991 \qquad (8)$$

Simultaneously with increasing the cracking probability of AlSi5Cu1alloy tensile strength R_m and fracture toughness K_{Ic} decrease (see Figs. 8 and 9). These relationships are described by:

$$\overline{R}_m = 418 - 34{,}3\cdot \overline{V_V}(F); \quad r = 0{,}94 \qquad (9)$$

$$\overline{K}_{Ic} = 32{,}03 - 2{,}8\cdot \overline{V_V}(F); \quad r = 0{,}954 \qquad (10)$$

On the basis of results (Tab. 3 and Fig. 6) it was found, that during loading of each of four microstructure variation of AlSi5Cu1 alloy (A, B, C and D), eutectic silicon crystals of the largest sizes crack in the first place. Basing on Hall Petch's equation, an influence of the fractured crystals sizes *d(P)* on strength of AlSi5Cu1 alloy, as a function R_m and K_{Ic} of $d(P)^{-1/2}$ (Fig. 10-11) was evaluated. The relationships shown in these figures are described by:

$$\overline{R}_m = -155{,}7 + 1134{,}4\cdot \overline{d}(F)^{-1/2}; \qquad r = 0{,}940 \qquad (11)$$

$$\overline{K}_{Ic} = -15{,}7 + 94{,}8\cdot \overline{d}(F)^{-1/2}; \qquad r = 0{,}973 \qquad (12)$$

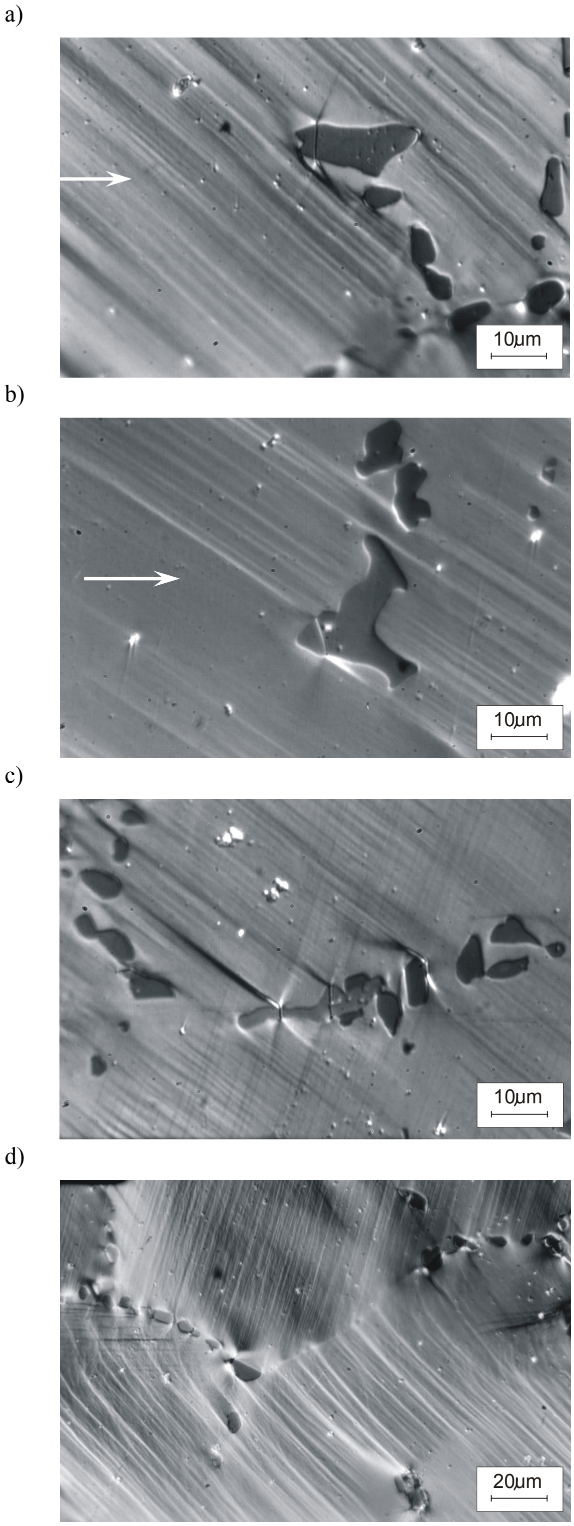

Fig. 6. Change of slip band direction and its intensity on eutectic silicon crystals. Fragmentation of crystals in orthogonal plane to tension direction (a-c)

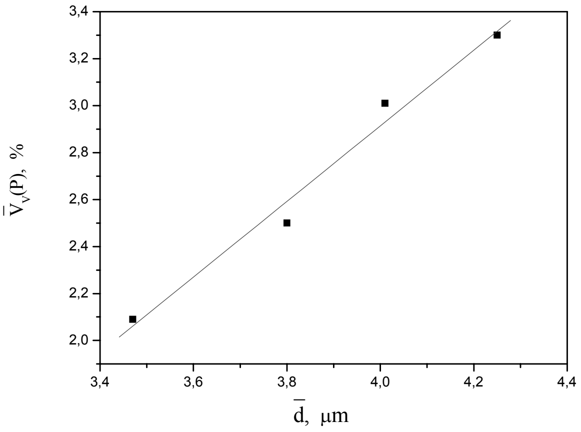

Fig. 7. Probability of cracking $V_v(P)$ of AlSi5Cu1 alloy as function of eutectic silicon crystals sizes d

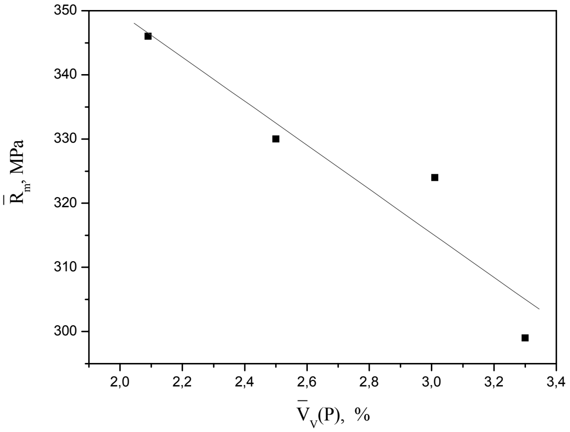

Fig. 8. Tensile strength R_m of AlSi5Cu1 alloy as function of cracking probability $V_v(P)$

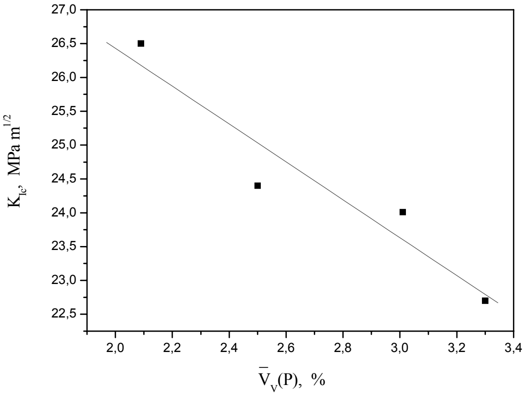

Fig. 9. Plane strain fracture toughness K_{Ic} of AlSi5Cu1 alloy as function of cracking probability $V_V(P)$

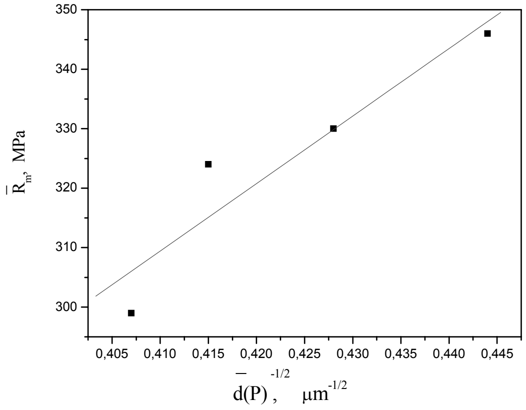

Fig. 10. Tensile strength R_m of AlSi5Cu1 alloy as function of fractured eutectic silicon crystals size *d(P)*

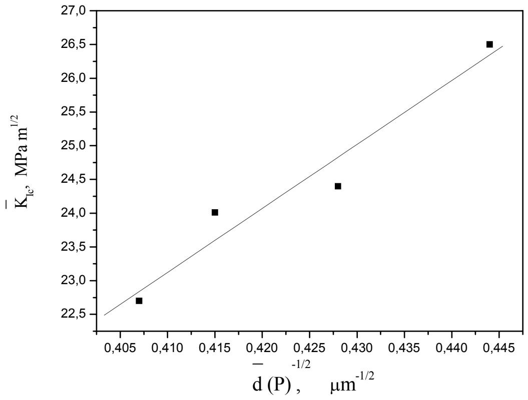

Fig. 11. Plane strain fracture toughness K_{Ic} of AlSi5Cu1 alloy as function of fractured eutectic silicon crystals size *d(P)*

4. Conclusions

1. The eutectic silicon crystals sizes have fundamental influence on mechanical properties of AlSi5Cu1 alloy – decreasing of crystals sizes results in increasing of mechanical properties. These linear relationships may be described by Hall-Petch type formula, using the following values of strengthening coefficient *k*: for tensile strength R_m, *k*=756; for yield stress $R_{0,2}$, *k*=356; for plane strain fracture toughness K_{Ic}, *k*=62,9.
2. The eutectic silicon crystals are strong barrier for the slip process under loading of AlSi5Cu1 alloy; development of macrocrack is proceeded by nucleation and propagation of microcracks in some of crystals (along planes perpendicular to load direction) –crystals of proportionally large sizes are cracking in the first instance (d_{Si} = 5-6 μm).
3. Increasing of relative volume V_V of the largest eutectic silicon crystals (d_{Si} > 5 μm) results in increasing of cracking probability of AlSi5Cu1 alloy at the smaller strain – alloy strength and fracture toughness are reducing according to Hall-Petch type relation. Presence of the large eutectic silicon crystals, "predisposed" to cracking, cause considerably reduction of tensile strength of the alloy with no significant change in its fracture toughness.

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