Microstructure and Fatigue Life of the A359 Alloy Reinforced with Al₂O₃ after Multiple Remelting

K. Pietrzak [a],*, A. Klasik [b], M. Maj [c],**, J. Sobczak [d], A. Wojciechowski [e]

[a] Institute of Precision Mechanics, Warsaw, Poland
[b] Motor Transport Institute, Warsaw Poland
[c] AGH University of Science and Technology, Faculty of Foundry Engineering,
Department of Foundry Process Engineering, Cracow, Poland
[d] Foundry Research Institute, Cracow
[e] Warsaw University of Life Sciences Faculty of Production Management and Production Engineering,
Warsaw WGW Green Energy Poland, Łomianki, Poland
Corresponding author: e-mail: * krystyna.pietrzakj@imp.edu.pl, **mmaj@agh.edu.pl

Abstract

The multiple direct remelting of composites based on the A359 alloy reinforced with 20% of Al₂O₃ particles was performed. The results of both gravity casting and squeeze casting were examined in terms of the obtained microstructure and mechanical characteristics. In microstructure examinations, the combinatorial method based on phase quanta theory was used. In mechanical tests, the modified low cycle fatigue method (MLCF) was applied. The effects obtained after both gravity casting and squeeze casting were compared. It was noted that both characteristics were gradually deteriorating up to the tenth remelting. The main cause was the occurrence of shrinkage porosity after the gravity casting. Much better results were obtained applying the squeeze casting process. The results of microstructure examinations and fatigue tests enabled drawing the conclusion that the A359 alloy reinforced with Al₂O₃ particles can confer a much better fatigue life behavior to the resulting composite than the A359 alloy without the reinforcement. At the same time, comparing these results with the results of the previous own research carried out on the composites based also on the A359 alloy but reinforced in the whole volume with SiC particles, it has been concluded that both types of the composites can be subjected to multiple remelting without any significant deterioration of the structural and mechanical characteristics. The concepts and advantages of using the combinatorial and MLCF methods in materials research were also presented

Keywords: Alloy, Composite microstructure, Properties, Recycling

1. Introduction

For many years, metal matrix composites (MMCs) based on light metals have been a potential source of application in the automotive and aerospace industries [1, 2]. Two reasons mainly account for this fact. Firstly, these are low-weight materials, and secondly they offer a number of favorable performance characteristics. As with all other materials and products, technological processes form a combination of various ideas that under given conditions aim at obtaining optimum material

characteristics. However, due to the dynamic technical development that has been underway for years, the growing number of post-production and post-operational waste is also a major problem. Hence, the initiative of circular economy (GZO) has emerged, according to which, based on EU requirements, the waste materials and products should be re-introduced into the production cycle after a recycling and/or material/product recovery. Detailed data on the recycling methods are provided for example in [6-10]. Most often, these methods include at least two steps and require significant financial inputs.

Considering this fact, the authors of this article promote a relatively inexpensive technique of recycling, the essence of which consists in multiple direct remelting. This method has been positively verified for a number of properties of the MMCs based on A359 alloy reinforced in the whole volume with SiC [11] or Al_2O_3 particles [12]. At the same time it should be clearly stated that this method requires a separate verification for each type of material. This cautiousness is due to the potential possibilities of the occurrence of some disadvantageous reactions at the metal matrix/ reinforcing phase interface. The said phenomenon takes place, for example, in the composites reinforced with SiC particles, if the required conditions of proper Si content in the composite metal matrix, casting temperature ranges and application of various reinforcement protective barriers are not respected [13, 14].

This article discusses the effect of tenfold direct remelting of the A359 alloy-based composite reinforced in the whole volume with 20wt% Al_2O_3 particles on both the microstructure (qualitative and quantitative assessment) and fatigue life. In the assessment of fatigue life, the authors used a modified low-cycle fatigue method (MLCF) [15, 16], particularly useful for quick estimation of fatigue parameters in the case of heterogeneous microstructures.

2. Test materials

The commercially available composite based on A359 alloy matrix reinforced in the whole volume with 20 wt% Al_2O_3 particles made by DURALCAN Company was used. It was produced by mechanical mixing the metal-ceramic suspension (vortex) and gravity casting. The chemical composition of metal matrix (A359 alloy) is presented in Table 1.

Table 1.
Chemical composition of A359 alloy

Compound [weight %]							
Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
8,6	0,12	0,03	0,007	0,46	0,01	0,11	residue

It was also found that the composite A359 + Al_2O_3 contains about 22% wt. of reinforcement (Al_2O_3) and about 3% by weight $MgAl_2O_4$ spinel. The composite was subjected to the ten times repeated remelting and ten times repeated casting. Two different casting processes that significantly vary in the time of the solidification of the metal-ceramic suspension, i.e. gravity casting to metal molds and squeeze casting, were used.

3. Microstructure

Sample microstructures of the examined A359-Al_2O_3 composite after the first and tenth remelting operation are shown in Figures 1 and 2. The photographs of microstructures in Figure 1 show the gravity-cast A359-Al_2O_3 composite, while Figure 2 shows the microstructure of the same composite after the squeeze casting process. The microstructures presented in respective photographs (Figs. 1-2) cannot be interpreted quantitatively. They are of an illustrative character only, adopting in their preparation the principle of choosing the "worst" area on the metallographic cross-section.
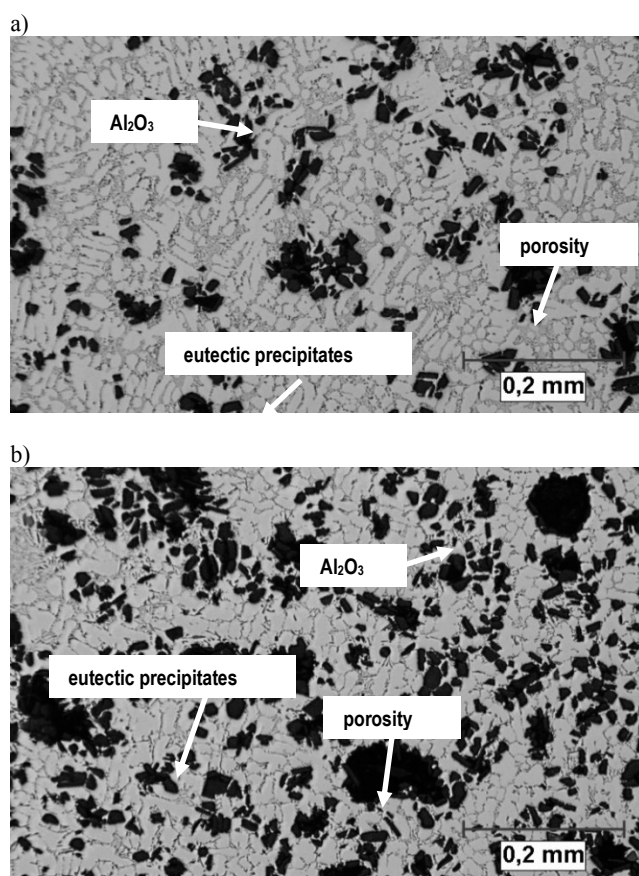
a)

b)

Fig. 1. Microstructure of A359-Al_2O_3 (20 wt. %) composite after the first (a) and tenth (b) remelting, gravity casting, 100x

In the case of the traditional gravity casting (Fig. 1), the occurrence of gas-shrinkage porosity is clearly noticeable. This defect has been effectively eliminated up to the 10th remelting operation using the squeeze casting technique (Fig. 2).
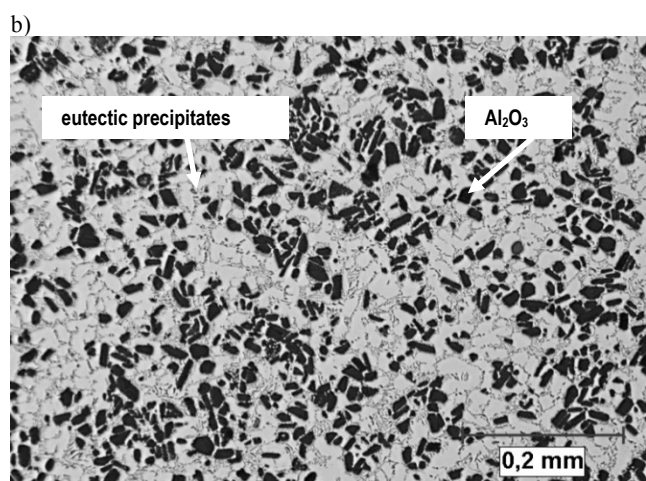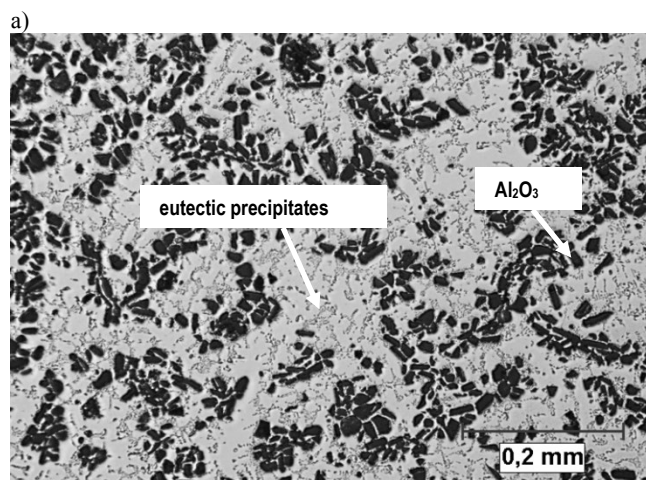
a)

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Fig. 2. Microstructure of A359-Al₂O₃ (20 wt. %) composite after the first (a) and tenth (b) remelting, squeeze casting, 100x

In order to determine how the microstructure of the A359-Al₂O₃ composite (20 vol.%) has been changing during the repeated remelting by both casting techniques, a quantitative metallographic analysis was performed determining different geometrical parameters of the composite microstructure after each remelting. As a result, it has been noted that special attention deserves the parameter called λ, which characterizes the mean free distance between the examined microstructure elements.

In the case of gravity casting, these elements include the Al₂O₃ particles, precipitates in the composite metal matrix and pores. In the case of squeeze casting, due to the absence of gas-shrinkage porosity, these are the Al₂O₃ particles and precipitates in the composite metal matrix.

According to the relationship $\lambda = (1-V_V)/N_L$, the λ parameter takes into account both volume fraction (V_V) of the measured elements as well as the estimator of their relative surface area (S_V), $S_V = 4N_L$ where N_L means the number of these elements per 1 mm of the test line. Changes in the value of the λ parameter as a function of the number of remelting operations are shown graphically in Figures 3 and 4.
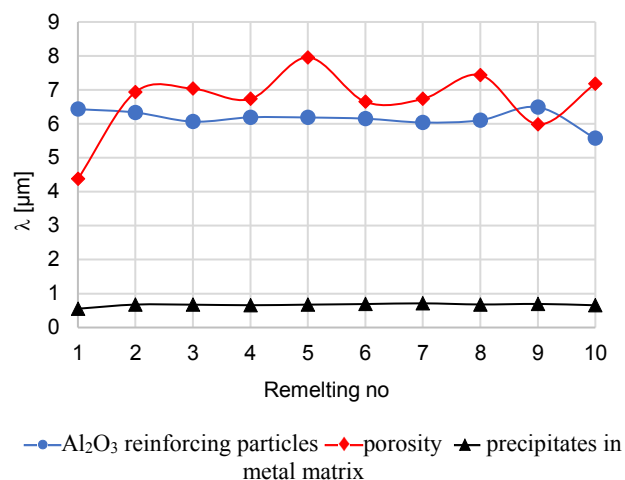

Fig. 3. Arrangement of Al₂O₃ particles, pores and precipitates in the composite metal matrix vs number of remelting operations (gravity casting)

The diagram presented in Figure 3 shows that in the case of gravity casting, after the first remelting, the mean free distance between pores is increasing and then up to the tenth remelting there are fluctuations in the values of the λ parameter in the range of 6 μm ÷ 8 μm.

These changes, noticed together with the increasing number of remelting operations in combination with the identified increase in pore volume (V_V) and the increase in both number of pores (N_A) per 1mm² and their size (F), indicate that local pore clusters are present in the microstructure. Their presence may negatively affect the mechanical characteristics of the composite.
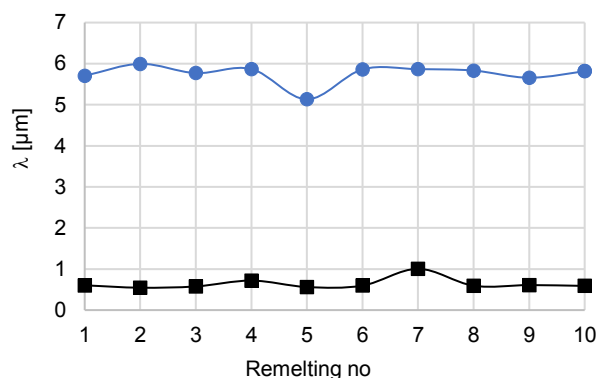

Fig. 4. Arrangement of Al₂O₃ particles and precipitates in the composite metal matrix vs number of remelting operations (squeeze casting)

In the case of squeeze casting, the distribution of both Al₂O₃ particles and precipitates in the composite metal matrix remains practically on the same level up to the tenth remelting (Fig. 4).

This effect, combined with the absence of gas-shrinkage porosity, should result in mechanical characteristics similar to those obtained in the starting material.

4. Mechanical properties

In fatigue life studies, a modified low cycle fatigue method (MLCF) [15, 16] was used.

It enables quick estimation of parameters from the Manson-Coffin-Morrow relationship:

$$\sigma_a = K' \, (\varepsilon_p)^{n'} \qquad (1)$$

$$\sigma_a = \sigma'_f \, (2N_f)^b \qquad (2)$$

$$\varepsilon_p = \varepsilon'_f \, (2N_f)^c \qquad (3)$$

where:

σ_a – the stress cycle amplitude,

σ'_f – so called, fatigue life coefficient roughly equal to the tensile strength R_m,

ε_f – the true permanent strain induced by stress σ'_f,

$2N_f$ – the number of loading cycles to specimen failure,

ε_p – the true permanent strain induced by $2N_f$ loading cycles, where: $\varepsilon = \ln(1 + \varepsilon k)$, and where $\varepsilon k = \Delta l_{permanent}/l_0$,

K' – the cyclic strength coefficient,

n' – the strain -hardening exponent for alternate cyclic loads,

c – the fatigue ductility exponent,

b – Basquin's coefficient.

Fatigue strength (Z_{go}) was determined from an experimental diagram (Fig. 5) developed for numerous materials, including pure metals, iron alloys and non-ferrous metal alloys [15].
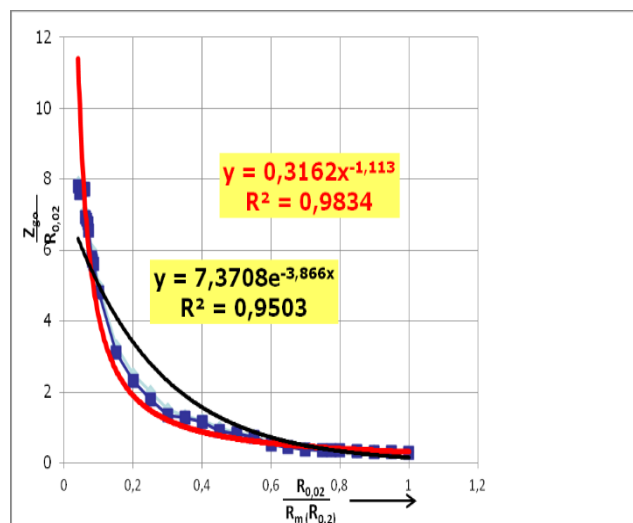

Fig. 5. The curve for fatigue strength determination [15]

The determination of fatigue parameters b, c, n ', K and ε_{max} was based on the following assumptions [15]:

- the elimination of uniaxial stress field under compression stresses is achieved using one-sided cycles performed in a fatigue stress test during tension,
- the permanent deformation caused by the assumed small number of cycles shows the same dependence on the cycle amplitude as the deformation occurring after sample rupture [15, 16],
- the determination of the above mentioned mechanical parameters can be based on the measurement data obtained each time on one sample only,
- the straight line courses derived from equations (2) and (3), presented in a double logarithmic scale, are determined by the position of points with the following coordinates: [ln 20, ln R_m] and [ln($2N_f$), ln(Z_{go})]: relationship (2), and [ln20, ln ε_f] and [ln($2N_f$), ln ε_z]: relationship (3),
- the assessment of the fatigue strength during rotary bending is carried out in accordance with [15, 16].

In addition to the mechanical parameters listed in this section and determined by means of the MLCF method, the accommodation limit (R_a) and the yield point ($R_{0,2}$) were also measured. The parameter (R_a) is defined as the stress over which the permanent deformation is no longer stabilized.

At the same time it is worth pointing out once again that both static mechanical parameters and those connected with low cycle fatigue are derived from the measurement data obtained each time on one sample only.

This is particularly important in the development of complex mechanical characteristics of the materials with heterogeneous microstructures.

The mechanical parameters of A359-Al_2O_3 composite determined by means of the MLCF test are shown in Figure 6 (gravity casting) and Figure 7 (squeeze casting).

A comparison of the curves shown in Figure 6 depending on the number of remelting operations leads to the conclusion that despite the application of gravity casting resulting in the occurrence of gas-shrinkage porosity (Fig. 1), only slight degradation in the mechanical parameters such as R_m, $R_{0.05}$, $R_{0.2}$, Z_{go}, R_a, K 'and E has been observed with the subsequent number of remelts.

The values of other mechanical parameters resulting from the low cycle fatigue test have remained practically on the same level irrespective of the number of remelting operations.

The use of squeeze casting allows the majority of the mechanical parameters to be maintained at the same level (Fig. 7). Only three parameters, i.e. K', c and E, are characterized by a certain scatter of their values (Fig. 7a, c).

As mentioned before, as a result of the squeeze casting process, the obtained microstructure of the composite is practically free of porosity (Fig. 2).

Thus, the reasons for the scatter of some results should rather be searched in the observed heterogeneity of the distribution of the reinforcing particles, and thus it should be recognized that the three aforementioned mechanical parameters, i.e. K ', c and E, are at the same time the most structurally sensitive.
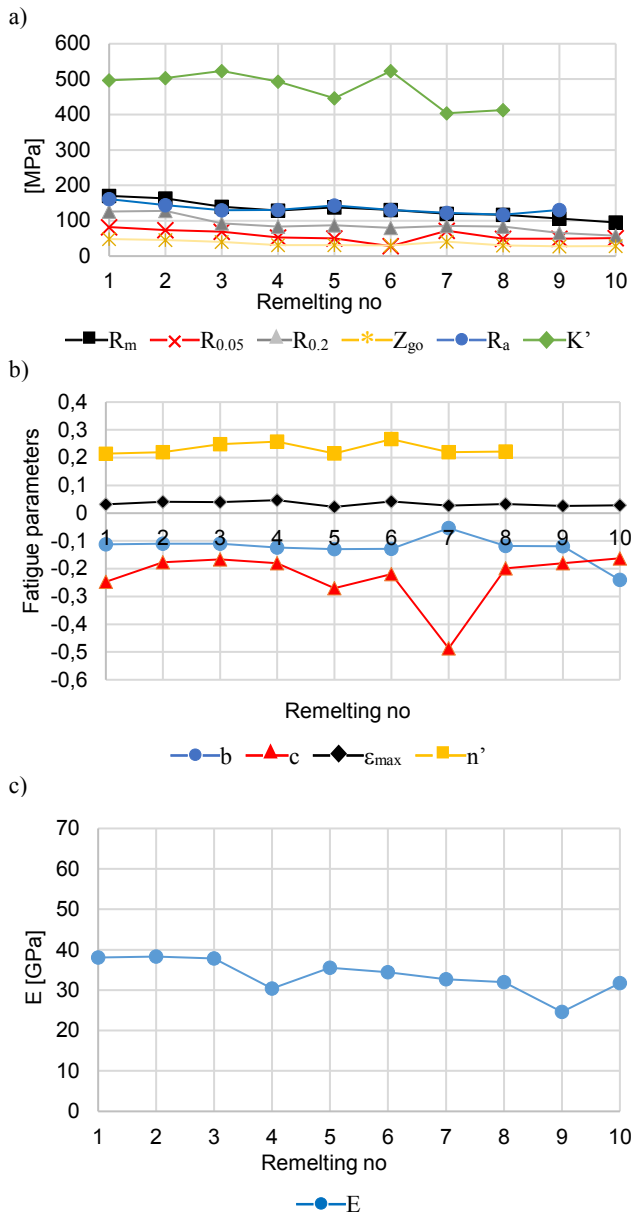
a)

b)

c)

Fig. 6 Mechanical parameters of A359-Al$_2$O$_3$ (20 wt %) composite vs number of remelts (gravity casting):
a) R$_m$-ultimate tensile strength; R$_{0.05}$-stress limit; R$_{0.2}$-yield point; Z$_{go}$-assessed fatigue strength; R$_a$-acomodation limit; K'-the cyclic strength coefficient, b) b-Basquin's coefficient; c- the fatigue ductility exponent; ε$_{max}$ - maximum allowable deformation; n'- the strain hardening exponent for alternate cyclic loads, c) E- Young modulus

Summarizing it should be underlined that the observed effect of the number of remelts on both microstructural and mechanical characteristics of the A359-Al$_2$O$_3$ composite can be considered insignificant.
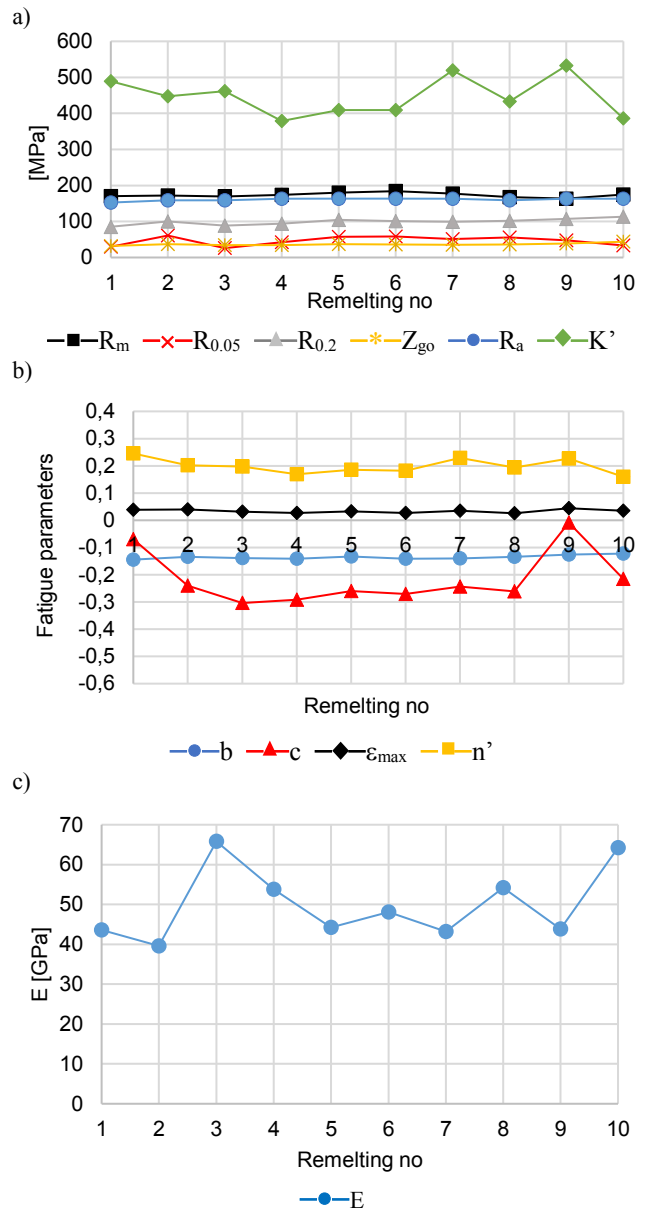
a)

b)

c)

Fig. 7 Mechanical parameters of A359-Al$_2$O$_3$ (20 wt%) composite vs number of remelts (squeeze casting):
a) R$_m$-ultimate tensile strength; R$_{0.05}$-stress limit; R$_{0.2}$-yield point; Z$_{go}$-assessed fatigue strength; R$_a$-acomodation limit; K'-the cyclic strength coefficient, b) b-Basquin's coefficient; c- the fatigue ductility exponent; ε$_{max}$ - maximum allowable deformation; n'- the strain hardening exponent for alternate cyclic loads, c) E- Young modulus

Positive results indicate that this composite can be subjected to multiple remelting as one of the recycling methods. This possibility is due, among others, to the high stability of the originally obtained metal-ceramic suspension, as was shown in [17].

5. Conclusions

Studies carried out allow formulating the following conclusions:

- the use of traditional gravity casting for each remelting causes gas-shrinkage porosity in the composite occurring after the first remelting,
- the changes in pore distribution characterized by the λ parameter combined with an increase in their volume fraction (V_V), the number (N_A) per $1mm^2$ and size (F) indicate the presence of local clusters of pores in the microstructure,
- introducing the squeeze casting method after each remelting completely eliminates the formation of gas-shrinkage porosity in the examined composite,
- irrespective of whether gravity casting or squeeze casting is used, the distribution of both Al_2O_3 particles in the composite and precipitates in the metal matrix, characterized by the λ parameter, remains practically the same as in the starting state,
- the performed tenfold remelting of $A359-Al_2O_3$ composite was observed to have no negative effect on its fatigue life,
- the MLCF method used to estimate different mechanical parameters, positively verified in previous own research on a number of casting materials [11, 15, 16], has been positively verified also in the present research carried out on the Al359-Al_2O_3 composite,
- the results obtained confirm once more the high stability of the initially obtained homogeneity of the metal-ceramic suspension, noticed also in previous own studies [17]. It remains stable not only after multiple remelting but also during preheating at a temperature much higher than the melting and casting temperatures recommended for the $A359-Al_2O_3$ composite [17],
- the multiple remelting of $A359-Al_2O_3$ composite can be treated as an alternative to other recycling methods that require more financial efforts.

Acknowledgments

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