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APPLICATION OF SINTERING CRITERION IN PRODUCTION OF AL-BASE COMPOSITES

ZASTOSOWANIE KRYTERIUM SPIEKANIA DO WYTWARZANIA KOMPOZYTÓW NA BAZIE ALUMINIUM

In the paper the theoretical sintering criterion was applied to check if sintering conditions of bearing aluminium matrix composites manufactured by recycling of communited aluminium and CuAl8 aluminium bronze chips, as reinforcing phase, determined experimentally were proper chosen. The criterion bases on the assumption that by conformability of plastic work of composites in metal working processes with critical values of the work needed for good junction of the particles determined in other simple test, the proper conditions of bonding process of particles can be achieved.

The composites were manufactured directly, without metallurgical process. The method of recycling contains: cleaning and communition of chips, premolding, hot extrusion and heat treatment during which the diffusion of copper and aluminium between matrix and reinforcing phase takes place and leads to create the hard intermetallic phases in soft matrix, the structure typical for bearing materials.

W pracy zastosowano teoretyczne kryterium spiekania do sprawdzenia czy warunki spiekania łożyskowych kompozytów na osnowie aluminium wytwarzanych poprzez recycling wiórów aluminium i wiórów brązu aluminiowego CuAl8, jako fazy umacniającej, określone doświadczalnie zostały dobrane poprawnie. Kryterium opiera się na założeniu, że poprzez uzyskanie zgodności pracy odkształcenia plastycznego koniecznej do wytworzenia kompozytu w danym procesie kształtowania z krytyczną wartością pracy odkształcenia plastycznego konieczną do dobrego zespolenia cząstek kompozytu określonej w innym prostym eksperymencie takie warunki są spełnione.

Kompozyty wytwarzano metodą bezpośrednią, z pominięciem procesu metalurgicznego. Metoda recyclingu obejmowała: czyszczenie i rozdrabnianie wiórów, wstępne formowanie, wyciskanie na gorąco i obróbkę cieplną, podczas której pomiędzy osnową i fazą umacniającą zachodzi wzajemna dyfuzja miedzi i aluminium która prowadzi do powstania twardych faz międzymetalicznych w miękkiej osnowie, struktury typowej dla stopów łożyskowych.

Keywords: bearing composites, sintering, criterion

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1. Introduction

Among the different production possibilities of composites, one of them is manufacturing them from waste products [1–8]. During the conventional recycling of the waste a lot of the metal is lost as a result of oxidation and the costs of labour and energy as well as the expenditures on environment protection raise the general cost of the manufacturing processes [6]. Among the different types of wastes, chips from the machining are probably most difficult to recycle by above mentioned conventional methods [2, 9]. In the case of aluminium chips, they have the fine fractions and small cross sections and remelting losses are very high. Thus the remelting process is a low recovery efficiency method for the recycling of aluminium and its alloys chips and great interest has been shown in chips recycling processes other than remelting [3, 4, 6, 10].

So different way of waste products recycling, consisting in the direct conversion of waste into compact metal without melting was elaborated. This kind of recycling can be applied not only to aluminium and its alloys [2, 6, 11–13] but also to iron [4, 5], copper and, to some extent, cast iron [4, 5]. In the case of the direct conversion of aluminium and aluminium-alloy chips into compact metal by extrusion, the waste is a part of the chips from which impurities cannot be removed (2%) and the extrusion waste is of up to 3%, thus ultimately 95% of the metal is recovered [6].

Direct conversion method in the case of aluminium and aluminium alloys base composites was applied to manufacturing composites reinforced by chromium [14] tungsten [12, 15, 16], aluminium oxide [17], carbon [18], silicon carbide [18], ferrochromium [19] and soft and hard aluminium bronzes [20–22]. The composites, with latter mentioned reinforcing phase [20–22] obtained fully by recycling of chips, have good tribological properties. The properties of these composites can be improved by heat treatment applied after hot extrusion. After heat treatment the distinct diffusion of elements is observed. As a result of diffusion, the aluminium matrix of composites was enriched in copper, and CuAl8 reinforcing phase in aluminium also. In this way the new phases γ_1, δ, ξ_2, η_2 and θ, according to Cu-Al equilibrium diagram are created and typical structure of bearing materials was obtained, it means the large, hard, load-carrying particles distributed in soft matrix. A structure like this cannot be obtained in the case of solid aluminium alloys. So the heat treatment of composites improved not only the tribological properties but the mechanical properties as well by difussion bonding, creation of new above mentioned phases and in the case of aluminium alloys base material, additionally by precipitation hardening, but the last effect is relatively small. During the heat treatment the grain growth was not observed because crushed surface layer of aluminium oxides distributed mainly on the grain boundary resists grain growth.

The benefits of the direct conversion of aluminium and aluminium-alloy chips into compact metal with good properties besides the high efficiency of metal recovering also include a possible reduction in the funds spend on environment oil protection as a result of the reduced consumption of ores and energy carriers, and less degradation of the natural environment because of reduction of air-pollution emission [23].

The following factors contribute significantly to the bonding of aluminium and aluminium-alloy chips: degree of granulation of the aluminium and aluminium-alloy chips, premolding parameters, stress and strain states, temperature, velocity and the lubrication in consolidation processes [23]. In the case of composites with additional introduced reinforcing phases the amount, form and size of these phases have an effect on the final properties of products also [12, 24]. This method is relatively simple and it limits itself to the comminution [25] and cleaning the chips, cold press moulding and consolidation of the chips by a hot working process [9]. The best consolidation process is hot extrusion. By employing this process, if enough high temperarure is applied, the sintering can be eliminated, since the latter proceeds with sufficient intensity during extrusion. The method can be used to extrude products in the form of bars, sections and pipes, which can be formed additonally by cold forming processes, as elongation of such composites is at least 10%.

The analysis of the effect of process parameters on the junction of particles can be performed experimentally or theoretically. Experimental investigation consumes a lot of time and money, but for theoretical analysis sintering criterion was elaborated lately [26].

The main aim of the paper is to check if sintering conditions determined experimentally are in good correlation with that definite theoretically by using sintering criterion. The criterion was applied to comminuted aluminium chips below 2 mm with 15% mass fraction of CuAl8 reinforcing phases. High-power ball mill with a horizontal axis of rotation filled with 20 mm-diameter hard bearing steel balls up to 45% of its volume was used for the mixing of above mentioned chips. The mixtures were subjected to compacting, heating and extrusion. The cold compacting was performed in a device with a floating die under the constant pressure of 400 MPa [20]. Then hot extrusion in temperature range of 500–525°C was employed to bring about diffusion bonding between particles by crushing the layer of oxides and actuating diffusion processes under a high pressure and high temperature. The density of composites after extrusion was over 99% [22].

2. Sintering criterion

The sintering criterion is based on the assumptions that on the bonding of particles two factors have fundamental effect, that are:

— the contribution of clear surface of particles, which are exposed during working processes as a result of the brittle surface layer fracture, to whole particle surface.

— the values of normal stresses acting on the clear surface of particles to bring them together on the atomic distance.

So the sintering criterion can be effected by both factors in the following form:

$$dW_s = f(\sigma_n, d\varepsilon_1), \tag{1}$$

where: dW_s — sintering indicator characterising the local quality of particles joining,
$d\varepsilon_1$ — increment of largest tensile strain,
σ_n — compression stress normal to the direction of the largest tensile strain.

For isotropic materials there is consistence of principal stress and strain directions and the normal compression stress σ_n is equal to the largest principal compression stress σ_3.

Taking into account that the greater is the outspread of the native surface the lower is the value of stresses that is needed for good sintering, the indicator characterising the local quality of sintering of particles can be described by the product of both factors as follows

$$dW_s = \sigma_3 d\varepsilon_1. \tag{2}$$

The good junction of the particles over the whole considered volume take place when sintering indicator W_s obtain the some critical value C_{cr}:

$$W_s = \int_0^{\varepsilon_1} \sigma_3 d\varepsilon_1 = C_{\mathrm{cr}}. \tag{3}$$

For axisymetrical metal forming processes of incompressible materials the component of principal strain state ε_1 can be expresses by other component of strain state ε_3

$$d\varepsilon_1 = -2d\varepsilon_2 = -2d\varepsilon_3. \tag{4}$$

Taking into account that sintered materials, especially during manufacturing, do not keep incompressible condition, that fact was expressed by introducing into relationship (4) the compressible coefficient α:

$$d\varepsilon_1 = -2\alpha d\varepsilon_3, \tag{5}$$

where: α — compressible coefficient.

Combining equations (3) and (5) the following relation is obtain:

$$W_s = \int_0^{\varepsilon_3} 2\alpha\sigma_3 d\varepsilon_3 = C_{\mathrm{cr}}. \tag{6}$$

That means that for the sintering of particles the defined unit work of the largest principal compression stress at the largest suitable displacement is needed. For the application of such a criterion the critical value of C_{cr}, which secures good junction of particles has to be known.

The parameter C_{cr} can be determined experimentally or analytically. Experimental determination of the parameter can be obtained by measuring the forces of compacting by plastic deformation of particles in some kind of processes with different degree of deformation at different temperatures and strain rates. Then by using finite element method (FEM) the components of strain state ε_{ij} and stress state σ_{ij} are determined and plastic work of the largest compressive stress at the proper displacement according to relationship (6) is calculated. The critical value of plastic work C_{cr} is the value of the flow stress — plastic work relationship at the point of outset of plateau (Fig. 1). This experimental method is very labour-consuming and strenuous. Much easier is to apply into analysis of sintering in metal working processes the theoretically calculated values of the C_{cr} parameter.

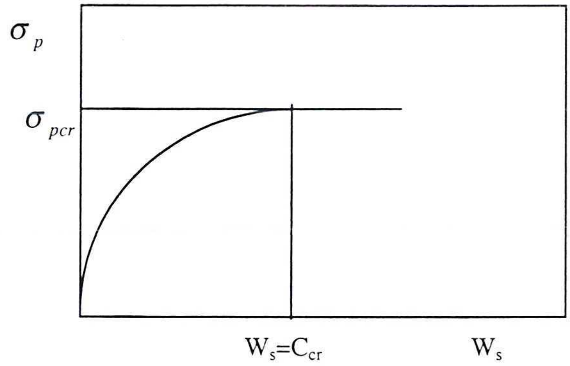

Fig. 1. Relationship between the flow stress and the unit plastic work needed in the manufacturing of the composite

The theoretical calculation of the of the parameter C_r is based on the assumption that a n-fold increase of the particle surface area is enough to fracture the brittle surface layer and to exposure the native structure for joining of particles. As a measure of the deformation degree of the particle, the change of its surface area is taken. Assuming the cylindrical shape of the individual particle, the degree of the deformation can be given by the relationship

$$S_p = \frac{2P_f + O_f H_f}{2P_o + O_o H_o}, \tag{7}$$

where: P_o, P_f — the surface areas of the initial and final cross sections of the particle, respectively,

O_o, O_f — the peripheral lengths of the initial and final particle cross sections, respectively,

H_o, H_f — the initial and final heights of the particle, respectively.

In the former criterion [26] only the side surface without the surface of cross sections perpendicular to cylindrical axis was taken into account. Since the volume V of the particle does not change, the following relationship are held:

$$H_o = \frac{V}{P_o},\ H_f = \frac{V}{P_f},$$

which allows to rewrite (7) as follows:

$$S_p = \frac{P_o}{P_f}\frac{2P_f^2 + O_f V}{2P_o^2 + O_o V} = \frac{P_o}{P_f}\frac{2P_o^2\left(\frac{P_f}{P_o}\right)^2 + O_o V\left(\frac{O_f}{O_o}\right)}{2P_o^2 + O_o V} = A\sqrt{R_p} + (1 - A)\frac{1}{R_p}, \tag{8}$$

where

$$R_p = \frac{d_o^2}{d_f^2} = \frac{P_o}{P_f} = \frac{O_o^2}{O_f^2} \text{ and } A = \frac{VO_o}{2P_o^2 + VO_o}, \tag{9}$$

where

d_o, d_f are the initial and final substituted diameters of the particles.

Unfortunately, the values of A depends on the initial shape of the particle. To avoid this inconvenience, the following average value of S_p is used:

$$S_p = \beta\left(\sqrt{R_p} + \frac{1}{R_p}\right), \tag{10}$$

where: β — the coeffcient equal to 0.5

To apply the above given analysis over the whole volume of extruded ingot the α — compressible coefficient have to be introduced into equation (10), so it takes following form;

$$S = \alpha\beta\left(\sqrt{R} + \frac{1}{R}\right), \tag{11}$$

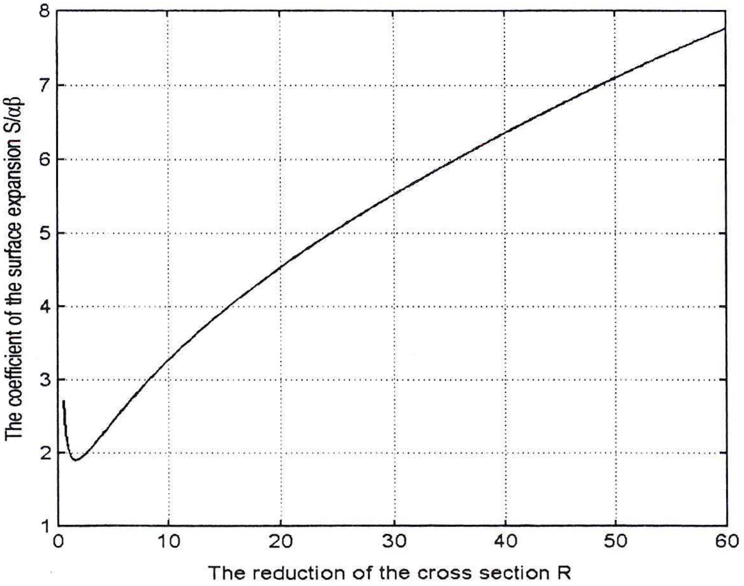

Fig. 2. The surface expansion $S/\alpha\beta$ as a function of the cross section reduction R

where R is the reduction of the cross-section of the ingot, S is the ratio of the initial surface of the ingot to the final surface of the product. From this relationship of the surface expansion $S/\alpha\beta$ as a function of the cross section reduction R (Fig. 2) it can be stated that the lower compressibility of the composites the smaller is deformation that is needed to obtain good junction of the particles. For investigated aluminium composite containing 15% mass fraction of reinforcing CuAl8 phase and the aluminium particle size below 2 mm, the compressible coefficient α should be equal to 0.7.

For a given surface expansion S, the limit strain needed for a good junction of particles in axisymetrical processes like extrusion can be obtained from the relation

$$\varepsilon_l = \ln \tfrac{d_o}{d_f} = \ln \sqrt{R}. \tag{12}$$

The value of R can be determined from the equation (11). To do it, this equation is transformed to the cubic algebraic equation

$$aR^3 + bR^2 + cR + d = 0 \tag{13}$$

with the coefficients $a = 1$, $b = -(S/\alpha\beta)^2$, $c = 2S/\alpha\beta$ and $d = -1$.

It is solved in the standard way. First auxiliary quantities

$$p = \frac{3ac - b^2}{9a^2} \text{ and } q = \frac{b^3}{27a^3} - \frac{bc}{6a^2} + \frac{d}{2a} \tag{14}$$

are introduced and the discriminant of (13) is calculated

$$D = p^3 + q^2. \tag{15}$$

It should be noted that p, q and D depend on $z = S/\alpha\beta$.

The relationship (11) is not a one-to-one correspondence between S and R in general but from the practical point of view the values of $z = S/\alpha\beta > S_{\min}/\alpha\beta \approx 2$ and $R > 2$ are interesting only. In this case, a one value of S corresponds to an exactly one value of R. Further, only such values of S and R will be considered.

Since then $p = p(z) < 0$, $q = q(z) < 0$ and $D = D(z) < 0$, the roots of (13) are given by formulas

$$R_1(z) = 2r(z)\cos(\varphi(z)/3) - b/3a,$$

$$R_2(z) = 2r(z)\cos(\pi/3 - \varphi(z)/3) - b/3a,$$

$$R_3(z) = 2r(z)\cos(\pi/3 + \varphi(z)/3) - b/3a,$$

where

$$r(z) = \sqrt{|p(z)|} \text{ and } \varphi(z) = \arccos \left| \frac{q(z)}{r(z)^3} \right|.$$

As the sought value of R, the greatest root of (13) is chosen, which gives

$$R = 2r(z) \cos \varphi(z)/3 - b/3a.$$

Since

$$\left| \frac{q(z)}{r(z)^3} \right| \to 1 \text{ or equivalently } \varphi(z) \to 0, \text{ as } z \to \infty$$

rapidly enough, the following approximate formula is proposed

$$R \approx Rap = 2r(z) - b/3a = \left(2\sqrt{z(z^3 - 6)} + z^2\right)/3 = \left(2\sqrt{(S/\alpha\beta)((S/\alpha\beta)^3 - 6)} + (S/\alpha\beta)^2\right)/3. \tag{16}$$

The R and R_{ap} values as a function of surface expantion are illustrated on the Fig. 3.

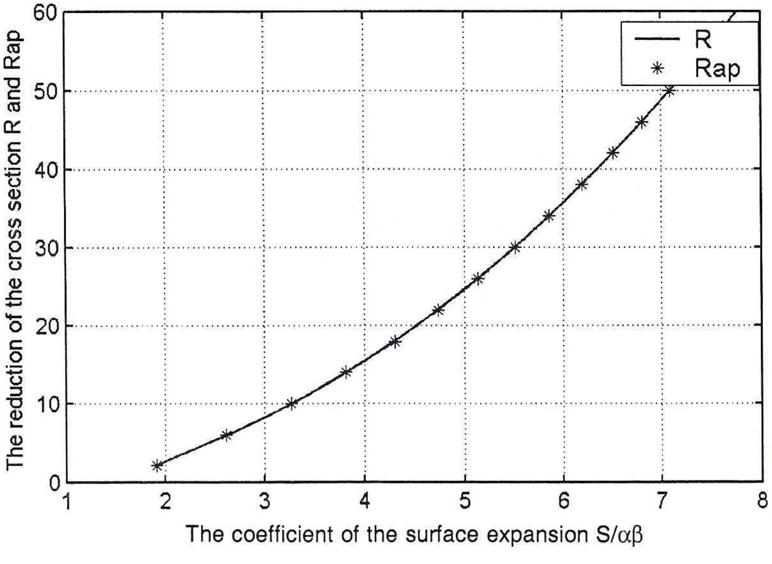

Fig. 3. The cross section reduction R and R_{ap} as a function of the surface expansion $S/\alpha\beta$

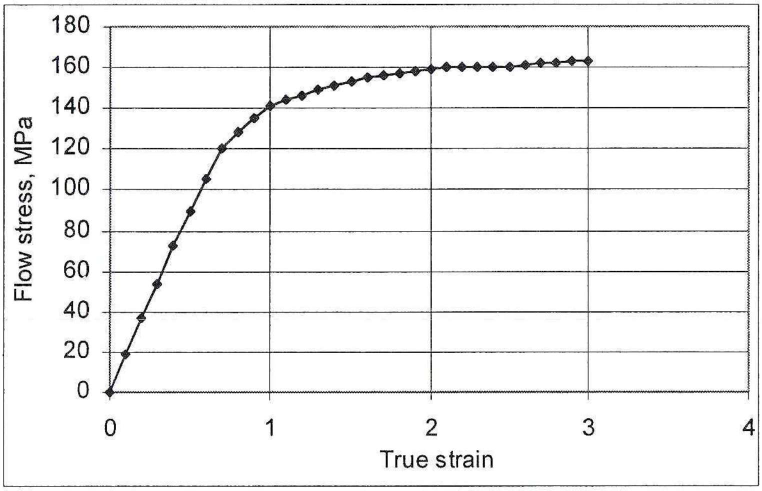

Fig. 4. True stress-true strain relation of aluminium composite containing 15% of reinforcing CuAl8 phase

For known stress-strain curve of aluminium composite containing 15% of reinforcing CuAl8 phase (Fig. 4) the calculation of critical values of the plastic work by using relationship shown in Fig. 2 can be performed:

$$C_{\mathrm{cr}} = \int_0^{\varepsilon_1} \sigma_p d\varepsilon_{\mathrm{int}} = W_s. \tag{17}$$

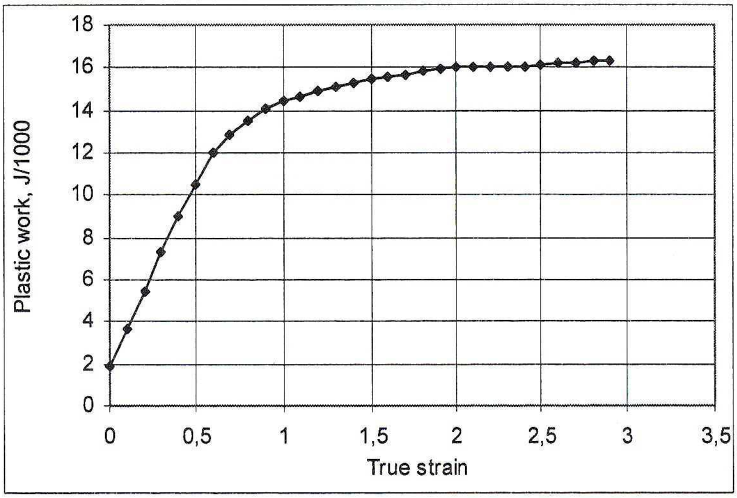

Fig. 5. The relationship between unit plastic work and true strain

The expansion of surface equal to 2,5 usually is enough to obtain good bonding of paticles that means from Fig. 2 reduction equal to about 6.25 and according to (11) such reduction in area meet elongation equal to 0.916. By integration of equation (17) the critical value of unit plastic work needed for good particles bonding determined from Fig. 5 is equal to about $14*10^{-3}$ J.

That is in good agreement with experimental results, where two values of reduction in area during extrusion were applied: 6.25 and 16. It was stated that even the lower value of reduction was enough for good bonding of investigated composite particles. It means that sintering conditions of bearing aluminium matrix composites manufactured by recycling of communited aluminium and CuAl8 aluminium bronze chips determined experimentally were proper chosen.

3. Conclusions

The simple sintering criterion [26], after small modification, for calculation of sintering conditions of aluminium base composite containing 15% mass fraction of reinforcing CuAl8 phase was applied. The criterion is based on comparison of the plastic work of composites in the extrusion process with critical values of the work C_{cr} needed for good junction of particles determined in the other simple test. It was stated that experimentally chosen conditions of composite sintering were in good agreement with that determined theoretically, so it means that experimental conditions of sintering was proper determined.

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