Hot deformation and mechanical properties of P/M Al special

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Abstract

Almost pure aluminum composite, P/M Al-special, with an average grain diameter of 1μm with oxides on the grain surface was produced by a powder metallurgy route. Billets were extruded on an indirect press at various temperatures and ram-speeds. Specimens made from an extruded profile were additionally annealed at 300ºC at various times. Hot workability of these various initial states was studied by hot compression tests in the strain rate range 0.01–10 s^{-1}, the temperature range 300–580ºC up to a strain of 0.9. Additionally tensile tests were carried out to determine the mechanical properties on specimens previously annealed at 300ºC. The oxide surface prevents grains coarsening during hot deformation and consequently excellent mechanical properties of the specimens annealed at a temperature of 300ºC were obtained.
Keywords: P/M 1080 Al composite, hot extrusion, annealing, hot compression, mechanical properties.

1 Introduction

Demands for weight reduction of parts applied in cars and aircrafts has lead to the replacement of conventional materials with lighter and stronger materials. Aluminum alloys have a great potential for this application but their weaknesses are too low strength and stiffness. On the other hand production of parts from metal-matrix composites which is based on the reduction of grain size is very promising due to their unique mechanical properties in comparison with coarse-grained materials [1–6].

Powder (P/M) and ingot metallurgy which include particle reinforcement mixing with solid or molten metal assure production of composites with

WIT Transactions on Engineering Sciences, Vol 72,
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/MC110211

improved mechanical, physical and thermal properties. Hard particles like ceramic, carbides, oxides or nitrides are usually finely dispersed in Al alloy matrix. For P/M the size of the powder can be in the range between several tens of nm to hundred µm, while the sizes of reinforcing particles are accordingly lower. Thus with P/M a finer microstructure with a uniform distribution of micro-constituents can be obtained which leads to mechanical properties, i.e. stiffness, strength and wear resistance, etc. which are usually better than those obtained for materials produced by casting procedures [4–16, 23–25].

Mechanical parts made from aluminum-matrix composites (AMCs) are usually produced by conventional hot deformation processes such as rolling, extrusion, forging, etc. Thus understanding of the behaviour of the material during hot working is essential for optimization of the intrinsic workability, control of evolution of microstructure, and for optimization of the production process. Hot workability studies revealed that AMCs are usually more sensitive to strain rate and temperature in comparison to conventional aluminum alloys. Namely, grain boundary sliding that takes place at higher temperatures and/or lower strain rates can lead to the formation of wedge-shaped cracks at grain boundaries. Additionally, the presence of hard particles in the softer matrix can result in plastic flow localization at the particle-matrix interface. Furthermore during hot extrusion of AMCs prior grain boundaries are usually removed due to diffusion, recovery, etc. that results in reduced mechanical properties. Increasing of grains during processing can be partly prevented by fine dispersion of ceramic particles. For such ultra-fine grained materials with a mean grain size of 1µm and below, different deformation mechanisms are operative than for coarser-grained materials. Namely in very small grains the accumulation of dislocations become difficult that leads to decreased ductility of fine grained AMCs, also at room temperature [5–23]. While for conventionally (by casting) produced AMCs the hot deformability has been studied in several publications [14–22, 26–30], hot deformation of P/M AMCs has found considerably less attention [5, 23–25, 31–34]. Only a few studies on P/M AMC using pure aluminum as a matrix exist. These studies report that pure Al may benefit more from brittle reinforcement particulates than Al-alloys [5, 35, 36].

The aim of this work is to produce a new fine grained P/M Al-special matrix composite on the base of almost pure Al with an oxide surface on grains aiming to prevent excessive grain coarsening during hot extrusion and followed by a hot deformation process as well as assessment of appropriate hot working parameters. Furthermore the mechanical properties were determined after the extrusion process as well as after various annealing times.

2 Experimental procedures

2.1 Material and characterization of microstructure

A JSM-5610 energy dispersive spectrometer from iXRF Systems Inc. with a digital processor 500 for chemical analysis of P/M Al-special was used along with a transmission electron microscopic (TEM, JEOL-2021) for microstructural characterization.

2.2 Processing of initial P/M Al-special

The P/M Al-special was produced according to the routes given in fig. 1. Powder was produced by Vacuum Powder Metallurgy, with a special grain powder process. Adding of various additives and lubricants is aimed to accelerate the diffusion processes in bulk material that represents the next step of preparation of powder mixture. After Rubber Isostatic Pressing (RIP) or Cold Isostatic Pressing (CIP) with application of a typical pressure of 100 MPa, the achieved density was 85%. Then follows the thermal preparation of billet (dehumidifying cycle) and machining of the billet to dimensions of ϕ274 mm. The hot extrusion was carried out on an industrial 35 MN indirect press. After extrusion the achieved density was 95% while following hot compression this value was 100% (see fig. 1).

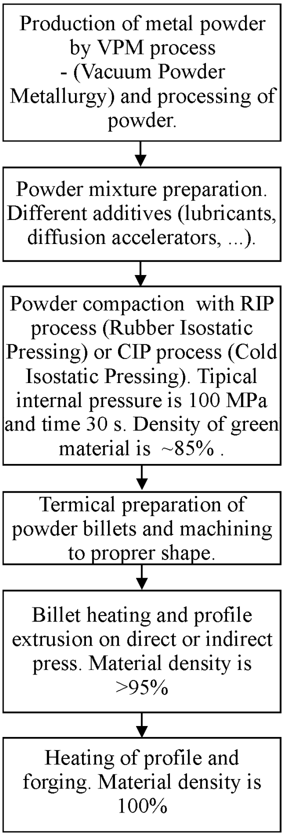

Figure 1: Processing routes for P/M 1080Al composite.

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2.3 Hot extrusion

Indirect hot extrusion at various billets temperature and extrusion speeds was employed to convert the processed powder to bulk material.

2.3.1 Extrusion of P/M Al-special on 35 MN indirect press

Initial powder billets of dimensions ϕ 274 x 1500 mm were hot extruded to a flat bar. Die dimension was 91.3 x 50.8 mm and extrusion ratio was 13.3. Maximum press pressure in the main cylinder is 250 x 105 Pa, which corresponds to a force of 35 MN. Billets 2 and 3 are heated in a die furnace (indirect) to 340ºC and 320ºC, respectively, while billet 1 was heated in an induction furnace to 420ºC. Ram speeds were in the range 3.89–8.87 mm/s. Other data applied at extrusion of P/M Al-special on the 35 MN indirect press are collected in Table 1.

Table 1: Technological data - Flat bar 90x50 (±0.9) mm, alloy P/M Al-special, indirect extrusion.

Technological data; die opening: billet dimension: ϕ 274 mm x 1500 mm, 91.3 mm x 50.8 mm, container dimension ϕ 280 mm, extrusion ratio: 13.3			
Billet material	P/M Al-special		
	1st billet	2nd billet	3rd billet
Billet length (mm)	500	500	500
Container temperature (ºC)	360	360	360
Billet temperature (ºC)	418	340	320
Ram speed (mm/s)	8.87	6.2	3.89
Puller speed - bar speed (m/min)	7.06	4.94	3.10
Press rest (mm)	50	50	50

2.4 Annealing

In order to investigate the influence of elevated temperature on recrystallization resistance, annealing tests were carried out at temperatures of 300ºC and employed at different times, i.e. 1, 5, 9 and 20 hours.

2.5 Hot compression and tensile tests

Hot workability was studied by hot compression tests. Cylindrical specimens of Rastegew type with dimensions ϕ=10 mm x 15 mm were cut from the extruded profile (3rd billet) so in non-annealed states as well as in annealed states, i.e. previously annealed at 300ºC for 1, 5, 9 and 20 hours, respectively. Hot compression of extruded material was carried out on a computer controlled servo-hydraulic machine, Gleeble 1500D, in the temperature range 300ºC to 570ºC, at five different strain rates (0.01, 0.1, 1 and 5 or 10 s^{-1}) up to a strain of 0.9, while for the annealed material from a production point of view only at a

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strain rate range 0.1–5 s^{-1}. The heating rate was 1ºC/s and the soaking time at compression temperature was 1 minute. For reduction of friction between the cylindrical specimen and the tool, and in order to avoid their mutual welding, graphite lubricant and tantalum follies were used. After deformation the specimens were water quenched. The conditions for hot compression testing are given in Table 2.

For determination of tensile strength and elongation at room temperature tensile tests were carried out on a Zwick Z400 according to standards (SIST EN 10002-1:2002, 5th edition, June 2002). Tensile specimens was cut out from the centre of the extruded bar, the working length of the tensile specimens was 50 mm with a diameter of ϕ=10 mm. Tensile tests were also carried out also on a AA 1050.

Table 2: Hot compression test conditions.

	Hot compression tests		
State of material	Temperature, ºC	Strain rate, s^{-1}	Strain range
Extruded	300–570	0.01–10	0-0.9
Annealed	300–570	0.01–10	0-0.9

3 Results and discussion

3.1 Composition and microstructures of initial materials

The bulk materials consist of 99.44 wt% Al, 0.034 wt% Si, 0.159 wt% Fe, while oxygen (0.363 wt%) is contained on the grain surface. Initial microstructures of loose and compacted powder P/M Al-special are given in figs. 2a-b, respectively. It is visible that the average diameter of powder grains is around 1μm and that the surface layer of grains consists of aluminum oxide (Al_2O_3) to prevent possible diffusion, recovery processes, i.e. to prevent grain growth during hot deformation.

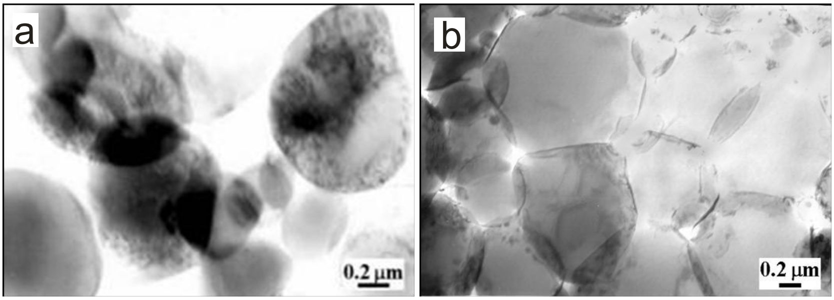

Figure 2: Initial microstructure of P/M Al-special: loose powder (a) and compacted powder with visible oxides on grain surface (b), TEM.

3.2 Indirect hot extrusion of P/M Al-special

The time courses of oil pressure in the cylinder for various billet temperatures as well as for ram speeds are shown on fig. 3. The lowest pressure of 215 x 105 Pa (177 bars) was obtained as expected at the highest billet temperature (418ºC) and highest ram speed (8.87 mm/s). On the other hand at the very beginning of the extrusion of the third billet almost the maximal oil pressure was achieved while the highest pressure at the lowest billet temperature (320ºC) and lowest ram speed (3.89 mm/s). The highest oil pressure 215 x 105 Pa (215 bars) was achieved at lowest billet temperature, i.e. at 320ºC.

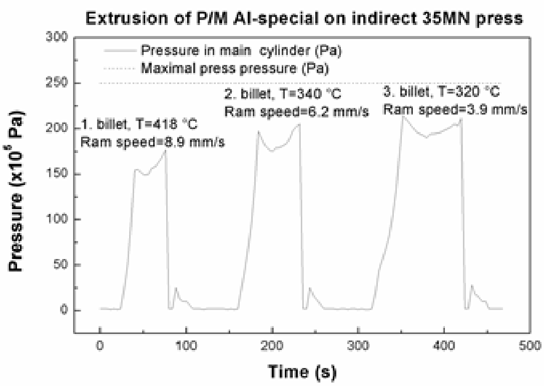

Figure 3: Time course of oil pressure in the cylinder during hot extrusion on the indirect press at various ram speed for P/M Al-special, 35 MN indirect press.

3.3 Hot workability of extruded and annealed P/M Al-special

Compression tests were carried out for extruded as well as for annealed states. On fig. 4a the typical microstructure of the extruded profile and on fig. 4b the microstructure of deformed samples which have been previously annealed for 20 hours at a temperature of 300ºC are presented. It is visible that the oxide surface on P/M grains is partly damaged but the average diameter of grains is only slightly increased in comparison to the initial state (ca 1µm, see fig. 2b). The figure clearly reveals that the oxide surface prevents grain growth.

Obtained flow curves for extruded P/M Al-special are shown on fig. 5. From deformed specimens and the shape of flow curves it can be seen that carrying out the hot deformation at lower strain rates (0.01–0.1 s^{-1}) is not appropriate since on specimens cracks occurred; this results in rapid fall of flow curves in the strain range 0.4–0.5 as can be seen for the strain rate of 0.1 s^{-1} on fig. 5, left. The behaviour can be ascribed to the usual problem of low-strain rate/high-temperature plasticity of P/M Al-alloys described in several studies such as in [37–41].

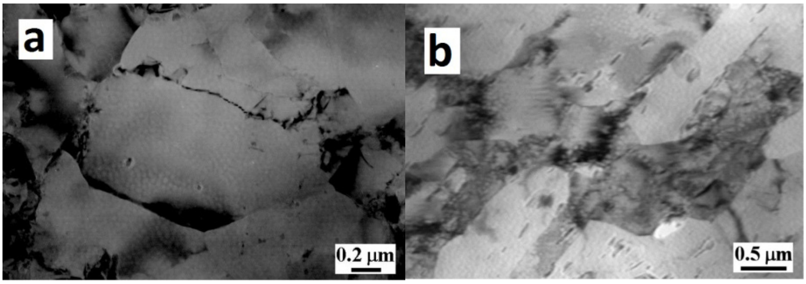

Figure 4: Microstructures of extruded P/M Al-special: extruded (a), and forged and annealed (b).

At higher strain rates the flow curves after achieving the maximal value at the very beginning of hot compression, i.e. in the strain range up to 0.03, the values of flow stress begin slightly to fall approaching a steady state (see fig. 5, right). Moreover, at higher strain rates (1–10 s^{-1}) the cracks did not occur that is expressed also by the shape of flow curves.

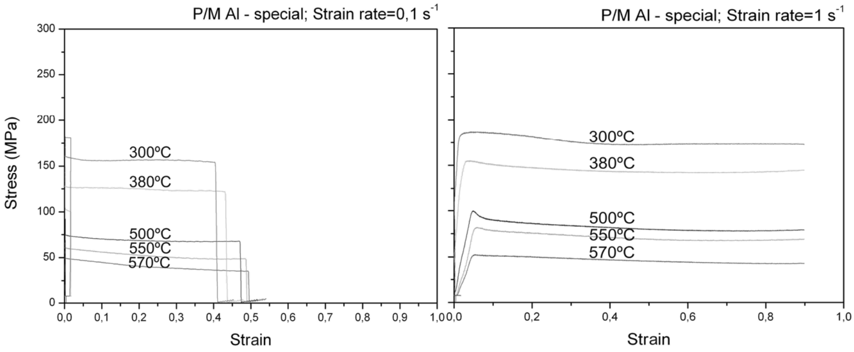

Figure 5: Flow curves of P/M Al-special (extruded state) at various temperatures and stain rates.

As mentioned the hot compression tests were carried out also for samples annealed at various times. The shapes of flow curves obtained after various annealing times and for a strain rate of 5 s^{-1} are similar to those obtained for the extruded state but in general their values decrease up to an annealing time of 5 hours (see fig. 6). It is visible that values of flow curves are considerably lower (about 15%) for annealed states in comparison to non-annealed states. During the extrusion a small percentage of the oxide layer on the grains are torn. This may allow re-arrangement of some grains with orientation changes. During annealing of extruded material the process of part polygonization starts. After one hour at 300°C material became stable since grain growth was blocked by oxides.

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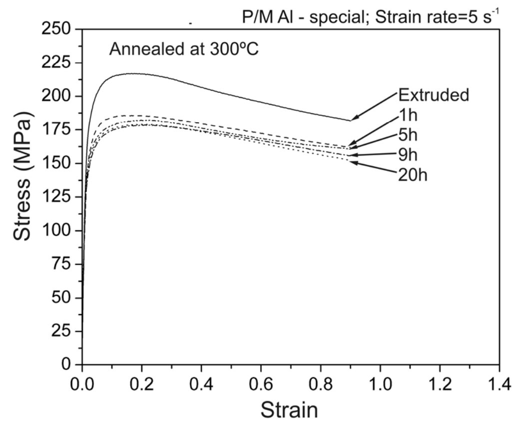

Figure 6: Comparison of flow curves between extruded and at various annealing times for P/M Al-special; strain rate 5 s^{-1}, annealing temperature 300ºC.

3.4 Obtained mechanical properties

The general presentation of the obtained mechanical properties, i.e. tensile strength and elongation, of P/M Al-special (indirect extrusion) is shown in fig. 7. The values of tensile strength of around 209 MPa and 205 MPa for the non-annealed and 20 hour annealed state were obtained, respectively. Furthermore, values for elongation for the non-annealed state were around 24% while for the 20 hour annealed samples these values slightly decreased and were around 23%.

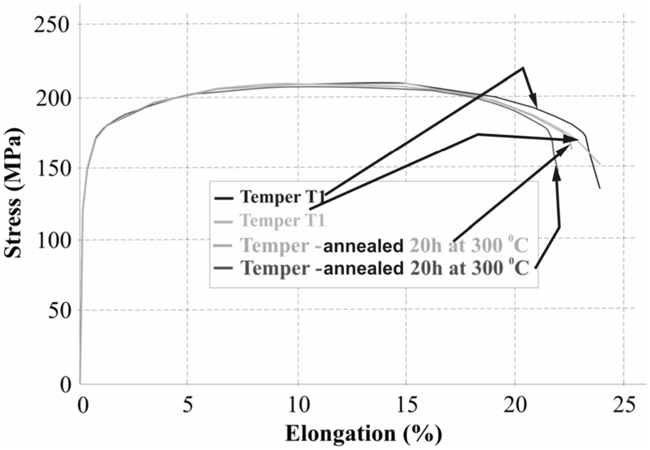

Figure 7: Tension curves σ vs. ε for P/M Al-special at various states and times of annealing.

For comparison for AA 1050 the values for strength were around 80 MPa and for elongation were around 38%. Thus around 2.6 times higher values for tensile strength and 1.6 times lower values for elongation for P/M Al-special in comparison to AA 1050 were obtained.

From the obtained results for P/M Al-special it can be derived that this material can be applied also at elevated temperatures. It is also worth mentioning that in our case grains consist only of almost pure Al and without particles in the matrix. Thus the achieved mechanical properties are also on a relative high level.

4 Conclusions

New P/M Al-special composite made from almost pure Al with an average diameter of 1μm and with oxides on the grain surface was developed. The achieved density after cold isostatic pressing was 84%, after hot extrusion 96% and 100% after hot compression. The P/M Al-special material exhibited a good combination of strength and elongation properties also at samples previously exposed to elevated temperature.

The produced P/M Al-special has a great potential to substitute the classical aluminum alloys and steels in the field of an elevated temperature working environment. The obtained values for tensile strength for P/M Al-special alloy are up to 2.6 times higher and for elongation around 1.6 times lower in comparison to values obtained for AA 1050 aluminum alloy produced by classical technology. The tensile strength of samples taken from extruded billet with an extrusion ratio of 13.3 reaches a value of about 209 MPa while achieved elongation was around 24%. The material exhibits good resistance against increasing of grain size at elevated temperature. After 20 hours of annealing the tensile strength slightly decreased and reached the value of 204 MPa. On the other hand the value for elongation remains almost at the same level, i.e. 23%. Extruded material exhibited low hot deformability at strain rates of 0.1 s^{-1} and lower, while at higher strain rates the compressed samples were crack free.

Acknowledgements

The authors gratefully acknowledge Martin Balogand and Karol Iždinský from Slovak Academy Of Sciences, Institute of Materials and Machine, Mechanics Račianska 75, 831 02 Bratislava 3, for their contribution towards analyzing the powder.

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