Proceedings of the 9th International Conference on Aluminium Alloys (2004)
Edited by J.F. Nie, A.J. Morton and B.C. Muddle

The Structure and Properties of Dispersion-Strengthened Mechanically-Alloyed Composite Materials Based on Aluminum Alloys

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Keywords: Al–Si, Al–Cu, Al–Mg, Al–Zn–Mg–Cu, Al–Si–Cu–Fe–Ni alloys, structure and phase composition, mechanical alloying, strengthening ceramic particles

Abstract

At different stages of mechanical alloying, the structure and phase compositions of dispersion-strengthened composite materials of aluminum alloys based on the systems Al–Si, Al–Cu, Al–Mg, Al–Zn–Mg–Cu, and Al–Si–Cu–Fe–Ni with aluminum oxide and silicon carbide were studied by methods of OM, SEM, TEM, electron probe microanalysis, and X-ray diffraction. Efficient use of initially large matrix and strengthening ceramic particles was first shown to be possible. Mechanically alloyed specimens had a homogeneous and disperse microstructure, a high hardness at room and elevated temperature, and a low linear coefficient of thermal expansion.

1. Introduction

Mechanical alloying (MA) is one of the most efficient modern techniques to produce dispersion-strengthened composite materials (CM). The potential of MA is its versatility to provide materials with a microstructure that is often impossible to obtain by traditional methods. Due to this, MA materials are distinguished by a unique combination of properties. In spite of its evident advantages, the method has several limitations [1, 2]. One of the major limitations, which impedes the widespread use of MA, is the considerable cost of the process.

Based on the analysis of numerous literature data and our own preliminary research, we proposed a way to reduce the cost of MA by bringing down the expenses for initial materials, e.g., by using the cheapest possible ceramic powders – strengthening elements – and also by at least a partial use of large particles of aluminum alloys as a matrix component. This is an original approach, and its efficiency was shown in our preliminary studies [2-4].

In view of this, the aim of this work was: (i) to systematically study the structural processes and phenomena, which occur during MA of initially large materials, and the subsequent consolidation of novel materials based on aluminum alloys and (ii) to establish the regularities of the effect of various process parameters of MA on the essential properties of materials.

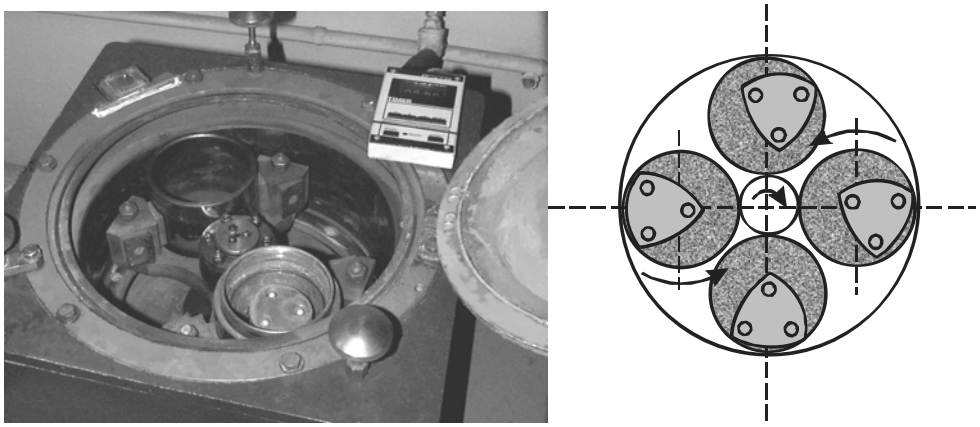
2. Experimental

Materials studied were based on model and commercial matrix aluminum alloys of the Al–Si, Al–Cu, Al–Mg, Al–Zn–Mg–Cu, and Al–Si–Cu–Fe–Ni systems (Table 1). These aluminum alloys were conventionally divided into two groups based on their structure in the as-quenched state: (i) multi-phase alloys the structure of which includes, besides aluminum solid solution, at least one extra phase which can be of various composition and origin (1–3) and (ii) single-phase alloys containing mainly aluminum solid solution (Al) of various composition in their structure (4–8).

Table 1: Composition of matrix alloys of CM studied

No	Alloy	Alloying elements, wt%						
		Si	Cu	Mg	Mn	Zn	Fe	Ni
1	AlSi11	11.3	–	–	–	–	–	–
2	AlSi12Cu2	12.0	2.2	0.2	0.3	–	0.8	–
3	AlSi11Cu2MgNi	10.5	2.1	0.9	0.5	–	0.5	0.8
4	AlCu4	–	4.4	–	–	–	–	–
5	AlCu3Mg2	0.1	3.2	1.5	0.01	0.01	0.15	
6	AlCu4Mg2Mn	–	4.4	1.5	0.7	–	–	–
7	AlMg5			4.7				
8	AlZn6MgCu	–	1.0	1.5		6.0	–	–

This division is conventional because at different MA stages the structure of single-phase alloys can be multi-phase due to the decomposition of oversaturated solid solution and, vice versa, due to the dissolution of excess phases the structure of multi-phase alloys can become single-phase. Large particles 2 to 5 mm in size, for instance, lathe chips, were used as initial matrix components for MA. The use of chips was aimed at investigating the possible utilization of wastes of, e.g., machine-building plants to produce CM. Chips of matrix alloys were obtained from castings which were cast into metal ingots at a cooling rate of ~ 10 K/s. Before chips were obtained, the castings were subjected to a heat treatment, which included a heating up to a temperature of 460–530°C, holding for 15–20 h and quenching in cold water. Silicon carbide powders of an average size 1, 10, and 40 μm, and also aluminum oxide of an average size 10 μm were used as strengthening ceramic particles. According to the data of X-ray diffraction analysis, the particles of SiC had the α-SiC structure; and the Al_2O_3 particles, the α-Al_2O_3 structure.



(a) (b)

Figure 1: Working space (a) and schematic (b) of a Gefest -11-3 planetary activator.

Matrix and ceramic particles were processed jointly for 2–300 min in a Gefest-11-3 planetary activator in hermetically sealed containers equipped with quasi-cylinder milling

elements in an argon atmosphere (Figure 1). The weight ratio of the milling elements and processed material in the activator was 10:1.CM specimens for studies of structure and properties were consolidated in two stages. First, under a pressure at room temperature up to a density not worse than 80%, and then at elevated temperatures but lower than the temperature of the onset of recrystallization of aluminum solid solution, which is the basis of CM. This procedure was used to obtain specimens 10–25 mm in diameter and 10–15 mm in height with a density no less than 98%. The structure of the granules, and also of consolidated specimens, after different treatment times in the activator was studied by a Neophot 30 light microscope, and JSM-35CF scanning and JEM-2000EX transmission electron microscopes. The phase composition, size of coherent scattering regions (CSR) and value of microdeformations in CM were assessed by a diffractometer.

3. Results and Discussion

A relative equilibrium between the processes of welding and decomposition of CM granules in MA was always considered to be hard to achieve if aluminum and its alloys were used as a matrix. In our case, the processing of most aluminum alloys independently and in the presence of ceramic particles in a planetary activator with quasi-cylinder milling elements proceeded well. At the early stages of processing, in most cases the fracture of large matrix particles dominated.

On the whole, two types of granules, differing in their shape and size, were observed at the early stages of processing aluminum alloys with ceramic particles:
• Particles of alloys having a high initial ductility due to the low content of brittle excess phases or low alloyability of solid solution had the shape of flat flakes. Their size in two dimensions considerably exceeded that in the third dimension. This behavior was characteristic of the alloys AlCu4, AlCu3Mg2, AlMg5, AlZn6MgCu and AlCu4Mg2Mn (see, e.g., Figure 2a).
• Particles of alloys containing a large amount of alloying elements and a large volume fraction of brittle phases were of much smaller size and, basically, equiaxial shape. This behavior was observed in alloys AlSi11, AlSi12Cu2 and AlSi11Cu2MgNi (see Figure 2b).
During the treatment in a planetary activator for 30–60 min the size of strengthening particles in all CM decreased tenfold and more, the shape became equiaxial, and their distribution along the volume of a granule became even (see Figure 2c, d).

As a result of a strong impact-attrition action, the structure of the matrix components changed significantly. Grain size and structural defects of aluminum solid solutions changed periodically due to the constant alteration of plastic deformation and recrystallization processes. The size of grain in this case was observed to decrease to a level controlled by effective obstacles (disperse phases and/or soluted alloying elements) for moving of dislocations and grain boundaries. The grain was the finer the larger the number of strengthening particles and disperse matrix phases, and the higher the alloyability of matrix solid solution. In all CM, the grain size of matrix solution after processing in a planetary activator for 60–300 min was several tens up to a hundred nanometers.

The phase composition of CM on the whole and of the state of (Al) at different stages of MA was assessed by a diffractometer.

The CSR values determined from X-ray patterns were compared with the values of average grain size measured from the electron-microscopic patterns of CM AlMg5–25%Al_2O_3 and AlCu4Mg2Mn–18%SiC (Table 2 and Figure 3).

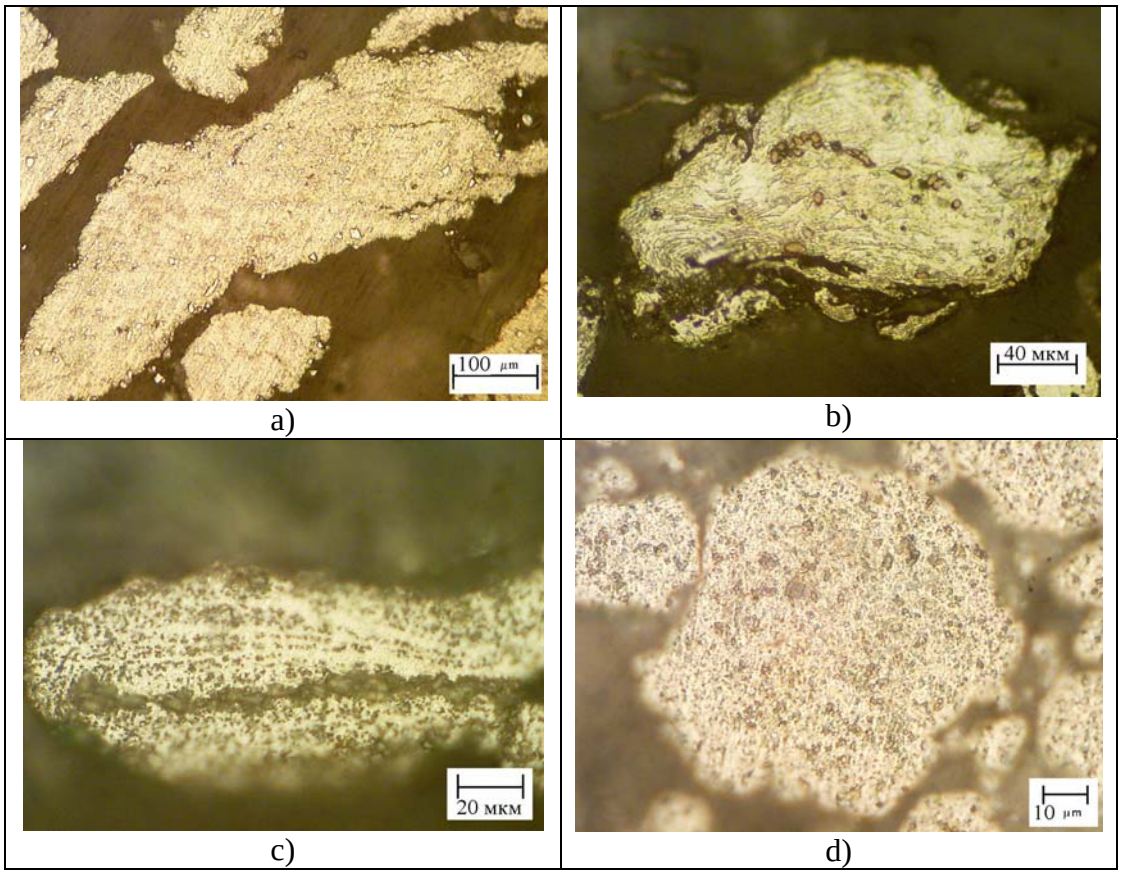


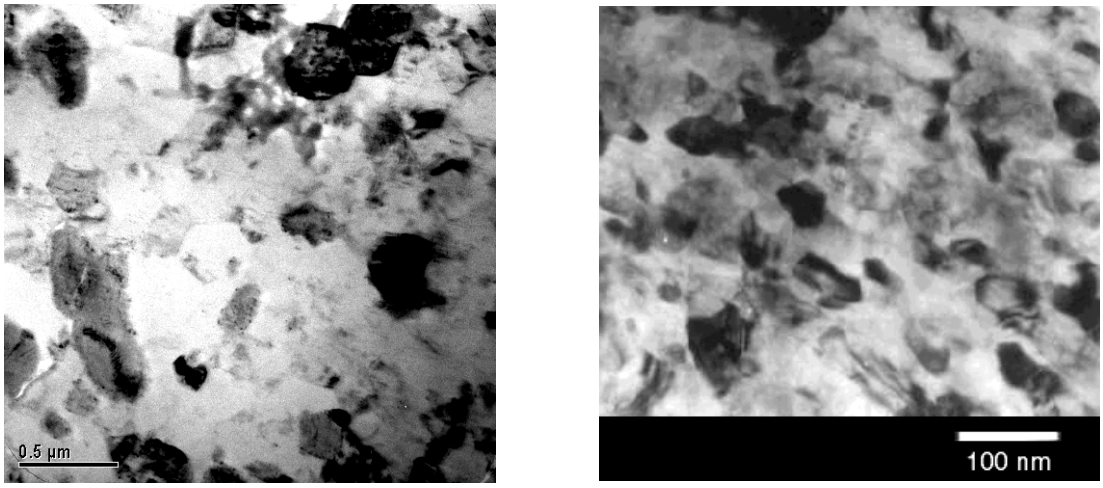
Figure 2: Structure of CM granules of AlCu4 – 5%SiC (a - 1 h treatment, b – 3 h treatment), and AlSi11–13%SiC (c – 1 h treatment, d - 5 h treatment).

Table 2: Experimental and calculated data of the assessment of size D and e in the composition material AlMg5–25%Al_2O_3.

Initial data		Calculation and experimental results	
Methods	HKL	D, nm	e, %
X-ray diffraction	(222)	73±9	0.04±0.03
TEM		73±4	-

The results are seen to coincide well, which suggests that X-ray techniques can be successfully used to assess the parameters of MA structures and only periodically they should be confirmed by expensive electron-microscopy studies.

Processing of materials of different compositions in a planetary activator led to a rise of granule Vickers hardness up to 2500–3500 MPa. Our studies showed a possibility to produce compact CM specimens based on various matrices by pressing at temperatures of 200 or 400°C, which guarantees a high density of consolidated specimens at an almost complete loss of individuality by the granules. During the consolidation of granules, due to the processes of recrystallization and decomposition of solid solutions, the hardness of the material decreases by 10–70%, depending on the volume fraction of strengthening particles, on the chemical and phase composition of the matrix.



a) b)

Figure 3: Electron-microscopy patterns of composite materials AlMg5–25%Al_2O_3 (a) and AlCu4Mg2Mn–18%SiC (b).

As a result, all CM obtained had high values of hardness at room and elevated temperature, low linear coefficient of thermal expansion (CTE) and high thermal stability.

Thus, for instance, the composition material Al11Cu2MgNi–20%Al_2O_3 after 120 min of processing in an activator and consolidation at a temperature of 400°C had the following properties: HV=2750±50 MPa, HB_1^{350}=240±20 MPa, the technical CTE within the temperature range of 20 up to 400°C was $18 \cdot 10^{-6}$ K^{-1} (see structure on Figure 4).

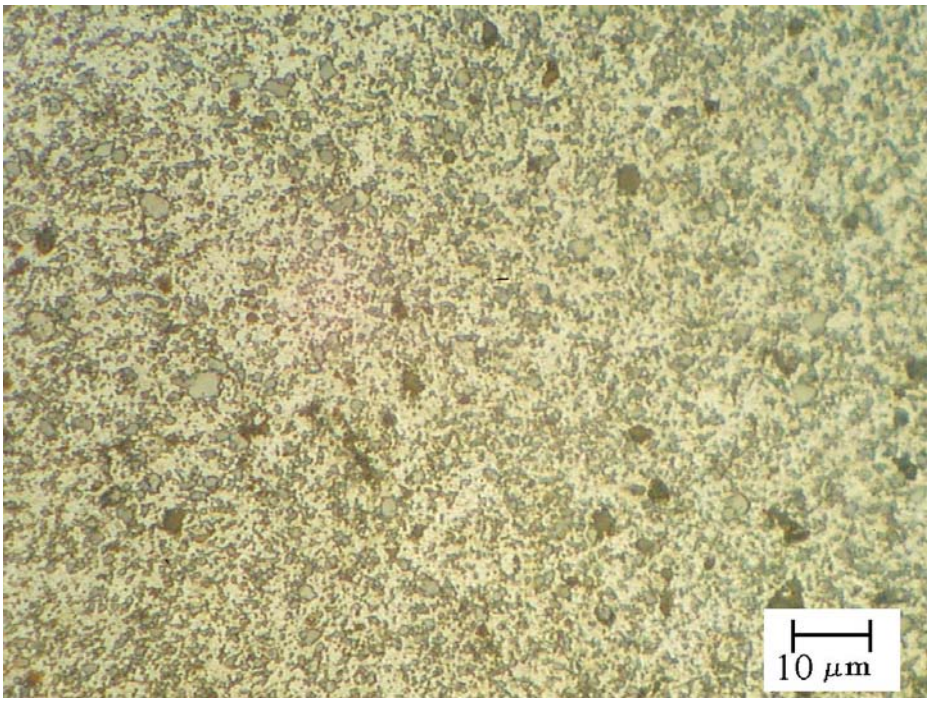


Figure 4: Structure of CM AlSi11Cu2MgNi–20%Al_2O_3 after 120 min of processing in an activator and consolidation at a temperature of 400^{O}C.

4. Conclusions

1. The possibility of efficiently using initially large matrix (500–5000 μm) and strengthening ceramic (10–40 μm) particles for MA was first shown using the

methods of optical, electron scanning and transmission microscopy; X-ray diffraction; and also using techniques of assessing essential physical and mechanical properties.

2. The treatment in a planetary activator was shown to lead to a gradual formation of a CM granule with a structure consisting of (Al) grains 25–150 nm in size and strengthening particles 10–1000 nm in size. The fine homogeneous structure of CM with higher volume fraction of strengthening ceramic particles and disperse matrix phases and/or higher alloyability of aluminum solid solution was achieved more faster. 3. Consolidated specimens of these CM were shown to possess a density higher than 98%, a high hardness at room and elevated temperature, and a low linear coefficient of thermal expansion.

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