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Influence of the cooling rate on the structure and mechanical properties of a cast alloy of Al—Mg—Si system

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An investigation of influence of the cooling rate on the structure and hardness of a new cast eutectic (α-Al + Mg_2Si) alloy of the Al—Mg—Si ternary system showed that the critical cooling rate at which a colonial eutectic structure disappears is ~10^5 K/s. The change-over from laboratory castings with a weight of 200g to commercial castings with a weight of 20 kg practically does not influence on the level of mechanical properties under comparable cooling conditions.

Introduction

At present, aluminum alloys are extensively used in the machine-building, aerospace, automotive, construction, and ship-building industries. At the same time, the trend to the replacement of steel components by components made of lighter alloys, in particular, aluminum alloys, increases. The authors propose a new approach to the development of competitive alloys based on using of ternary phase diagrams with the participation of aluminum, that have quasi-binary eutectic-type sections between an aluminum solid solution and intermetallic phases. Eutectic alloys the compositions of which are located on quasi-binary sections are solidified at a constant temperature which is higher than the melting points of alloys of limit binary systems. To provide a high level of the physical-mechanical properties due to the purposeful alloying of these alloys, in the matrix of these alloys, different systems of particles, which do not interact with the eutectic framework and are stable in some temperature ranges, are formed.

On the basis of the formulated principles, the authors developed a new class of cast aluminum alloys on the base of the quasi-binary section (α-Al + Mg_2Si) of the Al—Mg—Si ternary diagram (hereafter referred to as ASM alloys) which surpass traditional commercial Al—Si alloys by physical-mechanical and corrosion properties. The specific strength of the new ASM alloys is 1,5 times larger than that of steel 4135 (USA) [1—3]. It has been shown, that the advantages of the new ASM alloys rise with increasing temperature and testing time.

Properties of the new alloys in the form of castings with a mass of 200 g have been studied rather thoroughly. At the same time an investigation of the structure and properties of these cast alloys in variable sections where the cooling rate differs substantially is of scientific and practical interest. Moreover, from a scientific standpoint, an investigation of the new alloys obtained in the form of thin ribbons at a super-high cooling rate of the order of 10^5 to 10^7 K/s is of interest.

The aim of the present investigation is to study the influence of the cooling rate on the structure and mechanical properties of complexly alloyed cast eutectic (α-Al + Mg_2Si) alloys of the Al—Mg—Si ternary system.

Materials and Technique

Laboratory castings with a weight of 200 g were made in a resistance furnace in Al_2O_3 crucibles. The melt was poured in a copper mould of 25 mm in diameter. Castings with a weight of 20 kg were smelted in a graphite crucible of a diameter of 160 mm in an induction melting furnace of a power of 160 W with a TPChT-160 current source of high (24 kHz) frequency. The melt was poured into a water-cooled copper mould of 150 mm in diameter. Castings were made of pure charge materials and master alloys preliminarily heated to a temperature of 250 to 300 ºC to remove adsorbed moisture and prevent saturation of the melt with hydrogen. Smelting was performed in air using protective fluxes (75% LiCl + 25% LiF). At the end of each smelting, the melt was blown through with argon in the furnace. Furthermore, castings were made by pouring in a massive copper mould with a wall thickness of 31 mm (the diameter of castings was about 2,8 mm), and thin ribbons with a thickness 70 and 25 µm were obtained by the method of rapid solidification on a massive copper drum (the melt-spinning method). The rotation speed of the drum was about 24,5 m/sec.

Investigations were performed by metallographic, thermal, differential thermal, durometric, and X-ray diffraction (XRD) analyses, mechanical tensile and tribological tests.

Metallographic specimens were prepared using a standard technique. Their final polishing was performed using an aqueous suspension of chromium oxide as an abrasive. The etching of the metallographic specimens was carried out in a reagent with the following composition: 95% (vol.) of acetic acid and 4% (vol.) of perchloric acid. A metallographic examination was performed with the help of NEOPHOT-30 microscope and a Jeol Superprobe-733 electron probe microanalyzer.

The phase composition was studied with a DRON-UM1 diffractometer in CuK_α-radiation using a graphite single crystal as a monochromator.

The melting points of the alloys and critical points of phase transformation were determined with units for thermal and differential thermal analysis.

Hardness measurements were carried out by the Vickers method. The load on an indenter was 50 N. The microhardness of thin rapidly solidified ribbons was tested with a PMT-3 microhardness tester under a load of 0,2 N.

Short-term tensile test of cylindrical specimens were performed with recording of loading diagrams in the temperature range of 20—400 ºC using a generally accepted procedure which includes heating of specimens without loading for 0,5 h at a testing temperature with subsequent loading to fracture. The tensile rate was 10^{-3} s^{-1}.

The tribological test was carried out using an ATDK [4] original unit according to the sphere–plane contact scheme under conditions of reverse-forward slip of a spherical indenter over a flat specimen at a temperature of 20 and 200 ºC. The test was performed under a constant load (a quasi-stationary regime) and with the application of a variable load (dynamic regime). A silicon nitride Si_3N_4 ceramic spherical indenter of 8 mm in diameter was used. The sliding speed was 0,013 m/s, and a load applied to the indenter ranged from 22 to 78 *N*.

The results of experiments are designated by the subscripts “s” and “d” for static and dynamic regimes, respectively. Wear characteristics (I_s and I_d), which correspond to the depth of friction paths in regions of the quasi-stationary and dynamic loading, were used as criteria of assessment of the fracture mechanism of a surface.

Results and Discussion

It is known [5] that, depending on the cooling rate, the eutectic transformation proceeds by different mechanisms. In the present work, the influence of the cooling rate ($V_{cool.}$) of castings in the range 10^2—10^7 K/s was investigated (table 1). Micrographs of microstructures (manufacturing methods Nos. 1—4) are shown in fig. 1.

As it is seen from fig. 1, *a*, the structure of the casting of 25 mm in diameter is an assemblage of primary modified round dendrites of the α solid solution and the (α-Al + Mg_2Si) eutectic of lamellar morphology. The structure of the rapidly solidified casting of 2,8 mm in diameter is characterized by the presence of primary non-modified dendrites with axes of higher order (the loss of the stability of the form of growth of the dendrite takes place) and disperse eutectic (fig. 1, *b*). Under the cooling conditions of these two alloys, crystal growth is controlled by separation diffusion of atoms in the melt ahead of the crystallization front; in the process of crystallization, the colonial structures, which are characteristic of cooperative growth of eutectic, form.

At cooling rate of 10^5 to 10^7 K/s, which is characteristic of the rapidly cooled ribbon, cooperative growth of the eutectic cannot occur (fig. 1, *c*, *d*). Similar structures were obtained by super-rapid solidification of alloys of the Al—Cu and Fe—C systems under analogous conditions [6]. An abrupt

T a b l e 1. Microstructural features of ASM alloy specimens obtained under different cooling conditions

No.	Manufacturing method	Specimen size	$V_{cool.}$, K/s	Microstructure
1a	Smelting in an induction furnace (water-cooled copper mould)	Casting of 150 mm in diameter	10^2	Primary crystals of the α-Al phase (~18 µm) and a lamellar eutectic (the thickness of plates of the Mg_2Si phase is ~0,4 µm)
1	Smelting in a resistance furnace (copper mould)	Casting of 25 mm in diameter	$7 \cdot 10^2$	Rounded primary crystals of the α-Al phase (~14 µm) and a lamellar eutectic (the thickness of plates of the Mg_2Si phase is ~0,2 µm)
2	Rapidly cooled bar (copper mould)	Bar 2,8 mm in diameter	10^4	Primary crystals of the α-Al phase of dendritic shape (~4,2 µm; the dendritic parameter is ~3,5 µm) and an eutectic (the size of the Mg_2Si phase is ~0,2 µm)
3	Rapidly cooled ribbon (by casting on a copper drum of 390 mm in diameter)	Thickness of 70 µm	10^5—10^6	The Mg_2Si phase in the form of individual particles
4		Thickness of 25 µm	10^7	

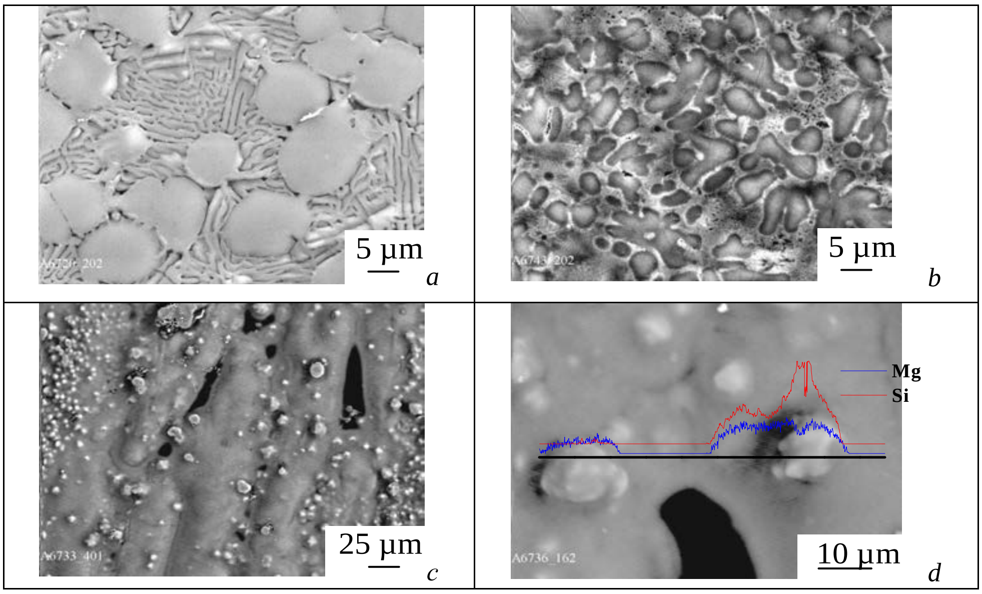


Fig. 1. Microstructure of a hypoeutectic ASM alloy obtained at different cooling rates: *a* — 7· 10^2 K/s; *b* — 10^4 K/s; *c*, *d* — 10^5—10^6 K/s; *d* — results of X-ray microanalisys.

T a b l e 2. Hardness of castings and ratio of phases (α-Al : Mg_2Si) according to XRD data

Method of production	State of specimen	Hardness, MPa	Ratio of phases α-Al : Mg_2Si
1	Cast	929*	92,7 : 7,3
	Annealing 300 °C/5 hours	1118*	90,9 : 9,1
2	Cast	1102*	92,9 : 7,1
	Annealing 300 °C/5 hours	1200*	—
3	Cast	1528**	92,9 : 7,1
4	Cast	1499**	96,9 : 3,1

*Load 5 kg; ** Load 20 g.

retardation of diffusion processes hinders growth of phases, as a result of which the sizes of critical nuclei decrease substantially, and their number substantially increases. Under these conditions, the colonial eutectic solidification becomes impossible and fine-grained mixtures of phases form. Such a disperse structure can be called a “structure of fine conglomerate of phases” [7—9].

Thus, the increase in the cooling rate favours to decreasing in the sizes of the structural components of the hypoeutectic alloy; the critical cooling rate at which the colonial eutectic structure disappears is ~10^5 K/s.

The phase composition of the alloy is characterized by the presence of α-Al and the Mg_2Si phase (table 2, fig. 1, *a*). In the structure of the thinnest rapidly solidified ribbon, besides the aforementioned phases, an amorphous phase is also presents (fig. 2, *b*).

It is interesting to note that as a result of the change-over from the traditional casting method to rapid quenching, the ratio of (α-Al : Mg_2Si) (specimens Nos. 1—3) remains practically unchanged (table 2), which indicates the high stability of the phase composition.

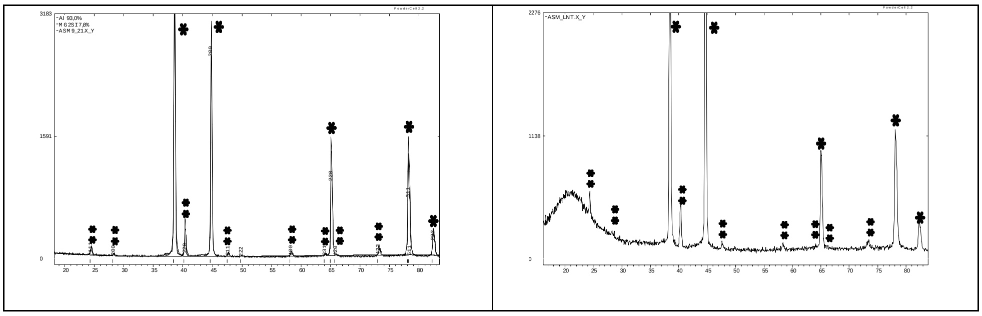


Fig. 2. X-ray diffraction patterns of rapidly solidified ribbons: *a* — ribbon with thickness of 70 μm with crystalline structure (* — Al, ** — Mg_2Si); *b* — ribbon with thickness of 25 μm with amorphous-crystalline structure.

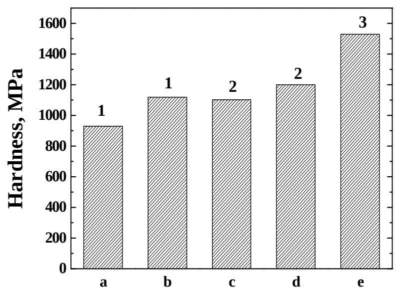
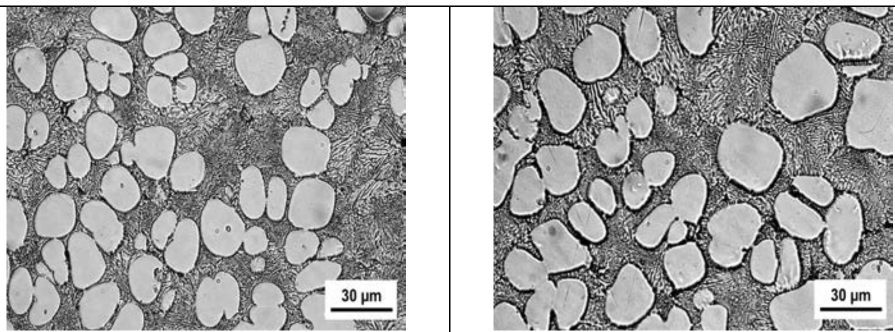


Fig. 3. The hardness of specimens of the ASM alloy which obtained under different cooling conditions: *a*, *c*, *e* — cast state; *b*, *d* — annealing 300 °C/5 hours. Number of specimen corresponds to table 2. The hardness of specimens Nos. 1 and 2 was measured under a load of 5 kg; the hardness of specimen No. 3 (rapidly quenched ribbon) was measured under a load of 20 g.

The hardness and microhardness of the investigated specimens are presented in table 2. The grain refinement of the rapidly quenched casting with a diameter of 2,8 mm (No. 2) leads to an increase in the hardness (fig. 3). The values of the hardness of the rapidly quenched ribbons of 70 and 25 μm in thick are close. From fig. 3 it is seen that the higher the cooling rate of the specimen, the higher the hardness.

In fig. 4, the microstructure of the laboratory casting with a weight of 200 g (fig. 4, *a*) and a witness sample obtained by smelting of the commercial casting with a weight of 20 kg (fig. 4, *b*) is given. Note, that in order to provide identical cooling conditions, the ingot with a weight of 20 kg was poured into the water-cooled mould.



a	*b*

Fig. 4. Microstructure of ASM-alloy in cast state: *a* — laboratory casting; *b* — witness sample obtained from a casting with a weight of 20 kg.

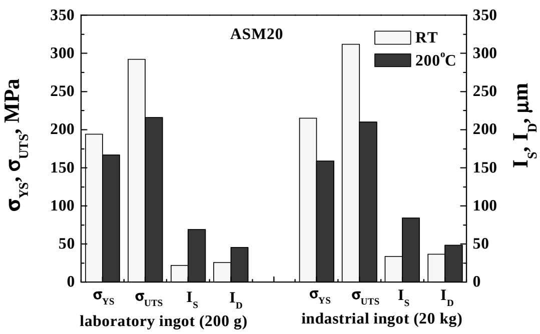


Fig. 5. Mechanical properties of ingots of weight 200 g and 20 kg.

The mechanical properties determined by tensile test and tribological properties of these alloys after the heat treatment are shown in fig. 5.

The data obtained indicate, that when certain solidification conditions are met, the level of properties of the ASM-alloy of the laboratory casting differ insignificantly from that of the casting with a weight of 20 kg.

Conclusions

The mechanism of pair eutectic growth in the α-Al—Mg_2Si system is realized in a wide range of cooling rates (to 10^4 K/s), which makes it possible to retain the eutectic structure of the alloys and their properties. At the same time, the ratio of the phases α-Al : Mg_2Si remains practically unchanged, which testifies to the stability of the phase composition. An increase in the cooling rate leads to the grain refinement of structural elements and an increase in the hardness.

The change-over from laboratory castings with a weight of 200 g (25 mm in diameter) to castings with a weight of 20 kg (150 mm in diameter) under comparable cooling conditions enables us to retain the level of mechanical and tribological properties of the new Al—Mg—Si cast alloy, which is particularly important for transition to commercial production.

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