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EFFECT OF THE CRYSTALLIZATION RATE ON THE STRUCTURE OF INGOTS OF MODIFIED ALUMINUM ALLOYS

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INTRODUCTION

The formation of fine-grain homogeneous structure in ingots of aluminum alloys is one of the most important conditions for fabricating quality semiproducts. Several generations of metal scientists and founders have studied the special features of crystallization of ingots and developed methods for providing a fine-grain structure, i.e., methods for modifying the structure. We distinguish three kinds of modification [1], namely, (1) disintegration of primary dendrite grains and other products of primary crystallization (grains of the primary solid solution as applied to deformable aluminum alloys of the matrix phase), (2) changing of the internal structure of primary dendrite grains, and (3) changing the structure of the eutectics (for example, in silumin).

In the present paper we consider the method of disintegration of the matrix phase as one of the most important kinds of modification for deformable aluminum alloys.

The nature and mechanism of this kind of modification have been studied in many works beginning with the research of A. Cibula in the 1940s [2, 3], M. V. Mal'tsev and his coworkers (Yu. D. Chistyakov, L. Cubichek, and V. M. Glazov) in the 1950s [4–6], and ending with the later works of B. I. Bondarev, V. I. Napalkov, and V. I. Tararyshkin in the 1970s [7] and M. P. Borgoyakov and V. G. Kouloulin in the 1980s [8, 9].

These works show that the disintegration of the matrix phase in cast alloys is a result of the inoculating action of the particles of the intermetallic phases formed in liquid alloy or specially introduced before the crystallization of the base (matrix) phase.

Numerous technological factors have been shown to influence the modification, for example, the method of the introduction of the modifier, the casting temperature, the temperature of heating before casting, and the cooling rate in crystallization.

Today the modifiers are chiefly introduced by two methods, namely, (1) in the form of an addition alloy (in pigs) together with the other components of the charge (aluminum,

some pure metals, for example, copper) into the melting furnace where a homogeneous melt is prepared, i.e., a liquid solution of all the alloying components in aluminum including the modifying ones (the content of which does not commonly exceed hundredths of a percent), and (2) by continuous feeding of alloying bars into the mold or the distributing box in casting of ingots.

The principal difference between these two methods of introduction of the modifier consists in the following. In the first method the particles of the intermetallic phases that serve as nucleation centers for grains of the solid solution are formed in the alloy in the process of its crystallization, segregating primarily from the liquid phase. In the second method the particles of the intermetallic phases playing the role of crystallization centers arrive into the melt directly before the crystallization of the solid solution from the alloying bars in a ready form. Their size is determined by the size of the intermetallic particles in the bars and depends on interaction with the melt comparatively little, because the melt has a low temperature (the casting temperature) and the time of contact is short (measured in seconds). It is clear from this why the same effect of structure modification, for example, with titanium introduced in the form of bars, is attained at a lower titanium content in the alloy than when it is included in the composition of the charge. In the second case virtually all of the titanium is contained in the added bars in the form of intermetallic particles that are crystallization centers (when the bars are produced from granules, the particle size fluctuates between 0.01 and 1.5 μm [9]). The amount of the intermetallic particles is easily controlled by the feeding of the bars.

In the first method (introduction of the modifier into the charge) the intermetallic particles segregate incompletely under the conditions of nonequilibrium crystallization; a part of the titanium remains in the liquid solution and then passes into the solid solution. In this case the intermetallic particles segregate at a high temperature and in a coarser form.

It should be taken into account that the transition metals that serve as modifiers (Ti, Zr, Nb, Ta, etc.) tend to form supersaturated solid solutions with aluminum in crystallization, i.e., as the cooling rate in the crystallization increases, a

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larger and larger part of the modifier (for example, titanium) remains in the solid solution and a smaller and smaller part of it (in the form of segregated intermetallics) serves as crystallization centers.

The process of modification of the structure of ingots from aluminum alloys by alloying bars arriving into the liquid metal directly before crystallization, has the described advantages, and its use will undoubtedly widen. However, this process will not fully replace modification of alloys by introducing the modifier into the charge, and therefore the problems of improving this technology will not lose significance.

The present work was aimed at studying the effect of high cooling rates in crystallization on the structure and properties of aluminum alloys with a high content of transition metals.

METHODS OF STUDY

Aluminum alloys alloyed with zirconium (from 0.7 to 1.6%) or zirconium (0.28–1.43%) and chromium (0.33–1.55%) were melted with the use of aluminum of grade A99 as a base. From each alloy we fabricated cylindrical ingots with a diameter of 15 mm (the cooling rate $v_{\text{cool}} \cong 100$ K/sec) and 50 mm ($v_{\text{cool}} \cong 10$ K/sec) by casting them into a thick-walled steel mold. In all cases the casting temperature was 25–50°C higher than the liquidus temperature. It follows from the Al–Zr phase diagram [10] that in all the alloys the primary crystallized phase is Al_3Zr , which is known to produce an effective inoculating action on the formation of grains of the aluminum solid solution and should cause modification of the structure.

RESULTS AND THEIR DISCUSSION

By the data of [1, Fig. 1] the addition of 0.7% Zr into aluminum causes maximum modification of the structure. It seems that in that work the researchers used low cooling rates in crystallization of the alloys. The factor of the cooling rate changes substantially the modifying action of zirconium. Figure 1 shows the macrostructure of ingots 50 mm in diameter from alloys with 0.7 and 1.15% Zr. Both ingots have a fine-grained structure. The ingots with 0.7% Zr possess some surface zone with enlarged grains, i.e., the enhanced rate of cooling of the alloy suppresses the segregation of the inoculating Al_3Zr phase.

In ingots with a shorter diameter (15 mm) crystallized at a higher rate (about 100 K/sec) and bearing 0.7% zirconium the grains are coarse and nonuniform (Fig. 2a), the structure being virtually unmodified. In the ingot with 1.15% Zr the grains are mixed, i.e., zones of coarse structure can be seen against the background of a fine-grained structure (Fig. 2b). In the ingots containing 1.3% Zr or more the structure was uniform and fine-grained, and the grain size decreased with growth in the content of zirconium to 1.6% (Fig. 2c–e).

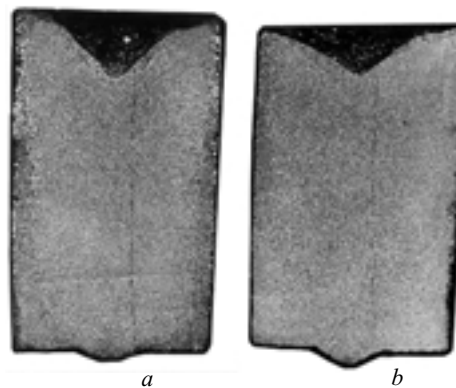


Fig. 1. Macrostructure of ingots of the Al–Zr system 50 mm in diameter: a) 0.7% Zr; b) 1.15% Zr.

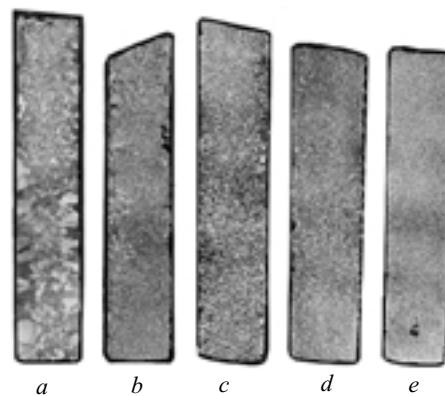


Fig. 2. Macrostructure of ingots from alloys of the Al–Zr system 15 mm in diameter: a) 0.7% Zr; b) 1.15% Zr; c) 1.3% Zr; d) 1.4% Zr; e) 1.6% Zr.

Thus, in alloys containing $\leq 1.15\%$ Zr at $v_{\text{cool}} \cong 100$ K/sec the larger part of the zirconium enters the solid solution. Only at $\geq 1.3\%$ Zr in the composition does the cooling process yield a sufficient amount of the intermetallic phase, serving as crystallization centers and causing modification of the structure.

A similar dependence of the effect of the cooling rate in crystallization on the modifying action was observed in ternary alloys of the Al–Cr–Zr system with various contents of chromium and zirconium. In these alloys the modifying phase, like in the binary Al–Zr system, is Al_3Zr .

It can be seen from Fig. 3 that with ingots 15 mm in diameter ($v_{\text{cool}} \cong 100$ K/sec) bearing 0.85% Cr + 0.95% Zr, zirconium enters the solid solution in crystallization and does not produce a modifying action. Only starting with 1% Zr is the structure modified. In the ingots 50 mm in diameter crystallized at a lower cooling rate the grains in the center disintegrate considerably even at 0.32% Zr (and 0.41% Cr) (see Fig. 4). At $\geq 0.83\%$ Zr in the composition the ingots have a fine-grained modified structure; small zones of coarse grains are seen on the surface only in the ingots with 0.83 and 0.95% Zr.

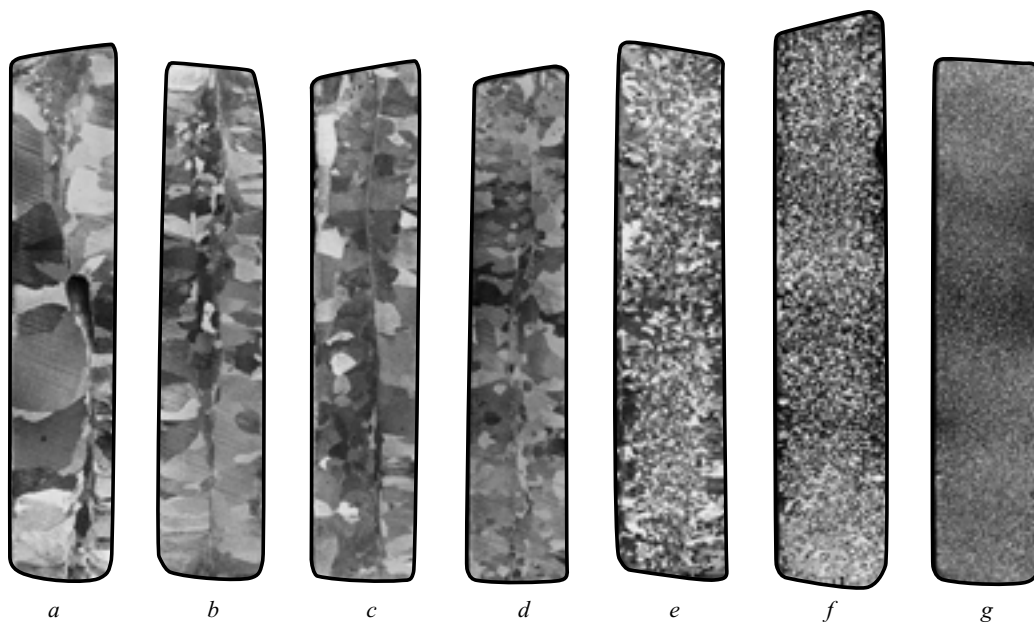


Fig. 3. Macrostructure of ingots 15 mm in diameter of alloys of the Al – Cr – Zr system: a) 0.33% Cr + 0.28% Zr; b) 0.41% Cr + 0.32% Zr; c) 0.55% Cr + 0.83% Zr; d) 0.85% Cr + 0.95% Zr; e) 1.0% Cr + 1.0% Zr; f) 1.25% Cr + 1.25% Zr; g) 1.55% Cr + 1.43% Zr.

The presented results of the estimation of the effect of the cooling rate in crystallization on the modifying action of additives of transition metals in aluminum alloys were ob-

tained in model alloys with a high content of transition metals not used in practice. But these examples reflect quite visually the role of the cooling rate on the modifying action. It

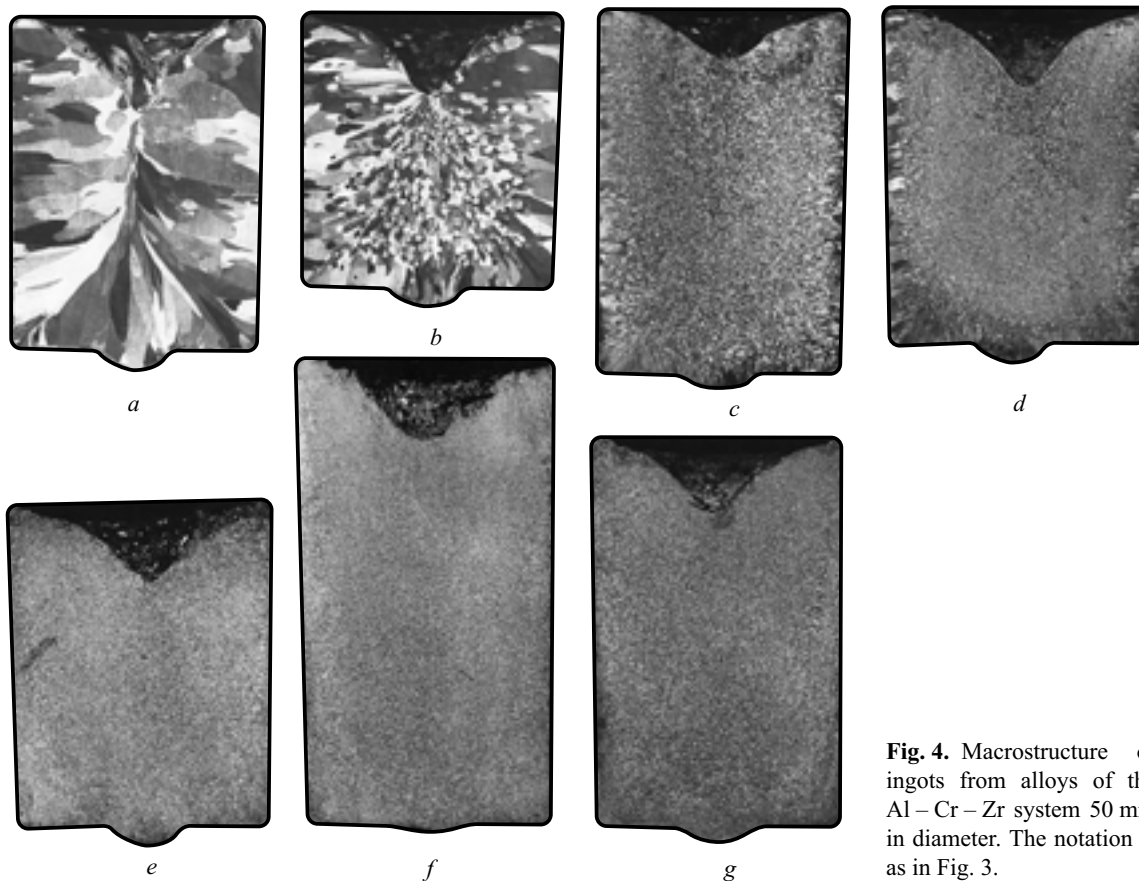


Fig. 4. Macrostructure of ingots from alloys of the Al – Cr – Zr system 50 mm in diameter. The notation is as in Fig. 3.

is obvious that at low additions of modifiers (Ti, Zr, etc.) actually used for modifying the structure of ingots of deformable alloys the role of the cooling rate in crystallization is similar.

In order to intensify the effect of modification, the alloy should be somewhat cooled before casting it into the mold (the degree of the supercooling should be chosen with allowance for the composition of the alloy and specific casting conditions), for example, by using a water-cooled cradle or a special near-tap box. These operations require an accurate observation of the temperature regime.

CONCLUSIONS

1. In modifying the structure of aluminum alloys for small ingots the content of the modifying element should be higher than for large ingots.

2. Some cooling of the melt before casting is expedient only in the case of modifying aluminum alloys, which do not contain other transition metals (manganese, zirconium, chromium) soluble in the solid aluminum with titanium. Rapid cooling in crystallization of alloys with manganese, chromium, or zirconium promotes the formation of supersaturated solid solutions of these components in aluminum and finally has a positive effect on the properties of deformed

semiproducts. In this connection a certain cooling of the alloy can be recommended only for various grades of technical aluminum and alloys of the type AD31, AK4-1.

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