Morphological features of crystal growth in the Al87Ni8Y5 alloy on rapid cooling of the melt under high pressure

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\textbf{A R T I C L E I N F O}

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\textbf{A B S T R A C T}

The authors have performed a comparative study of the structures of the hypereutectic Al87Ni8Y5 alloy (hereinafter indicated at.%) obtained by rapid cooling from the liquid phase during crystallization under pressure (from 1.8 to 2.2 GPa and 7 GPa), subject to temperature changes (from 1200 to 1800 °C) of the melt, through durametry, X-ray structural analysis and optical and electron microscopy. It is shown that under all the considered conditions of crystallization and the cooling rate of the melt of 10^3 K/sec, there are formed crystalline phases in the alloy. Dense homogeneous structures of the alloy with dispersed primary ternary aluminides Ni and Y of variable composition (with different contents of Ni and Y) or anomalously oversaturated α-Al-solid solution and modified eutectic, which have high hardness, are obtained.

1. Introduction

Multicomponent alloys based on aluminum, containing certain percent of transition (Fe, Ni, etc.) and rare-earth (Ce, Y, etc.) metals have long attracted the attention of researchers, due to their high physical and operational properties \cite{1,2}. At present, such alloys are produced in the form of thin ribbons (~50–100 µm) in the amorphous-nanocrystalline state. However, for a wider practical application, amorphous samples should not be ribbon-like, but rather of a bulk form. There is reason to assume that under the influence of high pressures (several GPa) and temperatures (up to 1500 °C) even at low melt cooling rates (up to 10^2 K/sec), it is possible to synthesize bulk amorphous alloys based on aluminum \cite{3}. In order to verify this assumption, we set the following aim: to investigate the effect of high pressures (up to 7 GPa) on the solidification of the glass-forming Al87Y5Ni8 melt. The choice of pressure values is caused by the fact that the range of high pressures, successfully mastered by industry, is limited to about 7 GPa. The mechanism of the effect high pressure produces on the structure and properties of alloys in different systems \cite{4–6}. As it turns out, for the chosen alloy, the effect of high pressure on the processes of solidification of melts has been studied thoroughly at neither low (~1 K/sec) nor high (10^3–10^6 K/sec) cooling rates.

2. Experimental procedure

The initial ingot, Al87Y5Ni8, has been obtained by alloying metals: aluminum-99.999, nickel 99.9, yttrium 99.99 (wt.%). Chemical analysis of ingots has revealed that the content of the main components corresponds to the specified compositions. The initial ingot contains pores.

The experiments have been carried out in the "toroid" chamber (Fig. 1) \cite{3}, using two types of assemblies: for indirect and direct heating. In indirectly heated samples, the sample has been isolated from high-pressure punches by a set of cylindrical insulating gaskets and placed in a hollow cylinder-heater. In this type of assembly, heating is limited to thermocouple (chromel–alumel) 50 mV (1250 °C) value, since a further increase in temperature leads to interaction of the thermocouple with carbon, as well as penetration of the thermocouple material into the sample. In direct heating, melting has been performed by passing an alternating current directly through the sample which is in contact with two Al(99.9) disc plates with a diameter and height of ~5 × 3 mm (there was no thermocouple). The melted alloy, immersed

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in a cylindrical tube of hexagonal boron nitride in the form of fine chips, melts, and the plate is fused at the point of contact, without being completely melted. As affected by high pressures and temperatures the compaction of metals and the mutual diffusion of the particles the alloy under study and aluminum occurs, which can lead to a blurring or complete disappearance of the interface. In our case, the interface is clearly visible (Fig. 2), and the composition of the alloy is not changed.

The boundary between the sample and the Al plate with direct heating (OM).

According to X-ray phase analysis, in the structure of sample No. 4 (see Table 1), two phases are discovered: \(\alpha\)-Al and the phase \(\alpha\)-Al + Al\(_{23}\)Ni\(_6\)Y\(_4\) is formed in the initial sample (Fig. 3a, inset), and at the melt cooling rate of 10\(^3\) K/sec, a modified eutectic of cellular type is formed in all samples (Fig. 3b–d). The composition of aluminides included in the cellular-type modified eutectic does not change with an increase in the melt cooling rate and corresponds to the stoichiometry of Al\(_{23}\)Ni\(_6\)Y\(_4\). The dimensions of the eutectic cells are 2–5\(\mu\)m, and the dimensions of the intermetallic phase of the eutectic, depending on the production conditions, are 0.1–0.5\(\mu\)m (light globules in Fig. 3b,c, inset), which represents a lower order of magnitude than in the initial state. Grinding of eutectic aluminides and changing the type of eutectic leads to an increase in its microhardness from 460 up to 1200–1300 MPa (see Fig. 4).

Thus, with this type of assembly in the “toroid” chamber, a simultaneous increase in pressure of up to 2.2 GPa and cooling rate of up to 10\(^3\) K/sec results in grinding of the matrix and primary aluminides Ni and Y, changing their chemical composition. Stable eutectic (\(\alpha\)-Al + Al\(_{23}\)Ni\(_6\)Y\(_4\)) is modified, which is accompanied by an increase in microhardness ~1.3–1.5 times compared to the initial state, depending on the conditions for obtaining samples.

3.2. Direct heating

According to X-ray phase analysis, in the structure of sample No. 4 (see Table 1), two phases are discovered: \(\alpha\)-Al and the phase

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Conditions for sample preparation</th>
<th>Microhardness (H_v), ((\pm 50) MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>by fusing metals in corundum crucibles in the Tamman furnace with the release into the cast-iron mold at atmospheric pressure</td>
<td>eutectic 900</td>
</tr>
<tr>
<td>1</td>
<td>1.8 GPa, 1 min, 1240 °C, indirect heating</td>
<td>eutectic 1250</td>
</tr>
<tr>
<td>2</td>
<td>2.2 GPa, 1 min, 1200 °C, indirect heating</td>
<td>eutectic 1150</td>
</tr>
<tr>
<td>3</td>
<td>2.2 GPa, 3 min, 1200 °C, indirect heating</td>
<td>eutectic 1200</td>
</tr>
<tr>
<td>4</td>
<td>7 GPa, 5c, 1800 °C, direct heating</td>
<td>(\alpha)-Al 850, eutectic 2700</td>
</tr>
</tbody>
</table>

* Approximate temperature.
corresponding to the AlxYyNiz compound, the composition of which is not clearly indentified. The α-Al contains 0.39% of Ni, Y is absent. According to the data of the reference [7], the solubility of nickel in aluminum is low: 0.01% at 500°C and 0.11% at the eutectic temperature. Rapid cooling from the melt (at rates from 10⁵ to 10⁶ degrees/sec and normal atmospheric pressure) increases the solubility limit of Ni in solid Al from 0.1 to 7.7%. Consequently, in the case of crystallization under high pressure of 7 GPa, the anomalously oversaturated Ni solid solution is formed at cooling rates several orders of magnitude lower (at 10³ K/sec). The remaining nickel and all yttrium are concentrated in the intergranular space, which is represented by a finely dispersed eutectic (α-Al + Al₂₃Ni₆Y₄) bordering the grains of the primary α-Al phase (Fig. 5a). According to local X-ray spectral microanalysis the composition of the alloy in the eutectic interlayer is as follows: Al 87%, Y 3%, Ni 9%. A detailed description of the structure evolution under high pressure and temperature conditions have been performed by EBSD analysis. Fig. 5b shows the DDE map and the spectra of changes in the size of grain-subgrains (dendritic cell) and the angles of disorientation of the boundaries of the fragments of the structure (Fig. 5c,d). According to SEM data, the average size of the α-Al phase fragments is ~6.5 μm. The average size of grain-subgrains on the DDE map is 2–3 μm. If we analyze the spectrum of grain boundaries, we see that there occur high-angle boundaries in the structure of sample No. 4 76%, and among low-angle boundaries those with disorientation of 2–5° prevail, located mainly within large grains. It can be assumed that they represent the boundaries between secondary branches of the dendritic cell dendrite forming. The microhardness of the eutectic sites in sample No. 4 increases 4 times as much compared to its initial value. Studies have shown the absence of defects and cracks in the sample.

The occurrence of the Al87Y5Ni8 alloy with the hypereutectic composition in the hypoeutectic crystallization region with this type of assembly in the «toroid» chamber indicates a nonequilibrium solidification of the solid phase under conditions of high supercooling at the crystallization front [8].

4. Summary

We have considered the combined effect of temperature, cooling rate of the melt and pressure on the structural-phase transformations during solidification of the Al87Y5Ni8 alloy. The positive role of high-pressure all-round compression is manifested in the elimination of pores in castings and an increase in the rate of melt crystallization. Under the influence of these factors, a dense homogeneous modified structure is formed in ingots. It has been established that in the pressure range of 1.8–2.2 GPa and cooling rate of 10⁷ K/sec, the grinding of primary intermetallics and a change in their composition is observed in the alloys of hypereutectic composition. Increasing the pressure to 7 GPa at the same rate of cooling of the melt, leads to an increase in supercooling at the crystal-melt boundary and changes the mechanism of solidification of the solid phase. In highly non-equilibrium crystallization conditions, the anomaly-oversaturated α-Al solid solution becomes the primary phase. According to the results of he EBSD analysis under these crystallization conditions, a dispersed structure of the dendritic type is formed (the grain size of the subgrain is 2–3 μm, the proportion of high-angle boundaries is 76%). Obtaining a dense homogeneous structure...
with dispersed aluminides Ni and Y or anomalously supersaturated α-Al solid solution and modified eutectic, ensures the growth of the alloy hardness and its strength properties due to solid-solution, grain-boundary and dispersion hardening.

The alloy under study is glass-forming. However, under the selected solidification conditions no amorphous phases have been detected. Guided by the available research data [3,9,10, etc.] on the effect of pressure on the melt solidification kinetics, we assume that in order to amorphize the structure of such eutectic alloys, the pressure range (at the same melt cooling rate) must be higher.

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References

[3] V.V. Brazhkin, Phase transformations in disordered condensed media at high pressure: Dist. ... Dr. Phys.-Mat. sciences in the form of a scientific report, Moscow, 1996.