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METALLURGY OF NONFERROUS METALS

Influence of the Microheterogeneity and Crystallization Conditions of the Al–50% Sn Alloy on the Mechanical Properties of Phase Components of the Ingot

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Abstract—Regularities of the influence of microheterogeneity and crystallization conditions of the Al–50 wt % Sn melt on the mechanical properties of phase components of the ingot such as the Young modulus and nanohardness are established. Measurements of these characteristics are performed by the nanoindentation method. The results of the investigation make it possible to reveal the mechanism of the effect of microheterogeneity and crystallization conditions of the melt on the pressure machinability of the ingot.

Keywords: Young modulus, hardness, nanoindentation, melt, viscosity, microdelamination, crystallization, microstructure

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INTRODUCTION

The mechanical properties of metallic alloys depend on the method of their fabrication. It is known that the destruction of the microheterogeneous structure of the melt and its transition into the state uniform at the atomic level (homogenization) by overheating to temperatures definite for each temperature are irreversible and lead to an increase in the level of mechanical properties of the ingot with the subsequent cooling and crystallization, even with rates of the order of 1–10 K/s [1]. Particularly, it is shown that the homogenization of the melts of the Al–Si system, which implies the heating of metal liquid above the branching point of the temperature dependences of its structurally sensitive properties (viscosity, density, surface tension, and resistivity) is accompanied by an increase in plasticity of cast metal by a factor of 10–15 with a simultaneous rise in its strength by 30–80% [2]. It is also established that heating metal liquid above the branching point of temperature dependences of its properties (homogenization) with the subsequent cooling and crystallization changes the microhardness of phase components of the ingot [1]. The question remains until open if the homogenization of the melt affects the mechanical properties of separate phase components of the ingot. The nanoindentation method makes it possible to perform mechanical tests in a microvolume [3]. It is known that the hardness tests by indentation or scratching can give almost the same information on the properties of metals as tension [4]. The mechanical properties of metal alloys depend not only on their sizes and morphology of inclusions of separate phases, but also on the level of their mechanical properties. Particularly, the elementary evaluation of the pressure machinability of a two-phase material implies the presence of information on the Young modulus (E) of separate phase components of the ingot [5]. The additional pressure caused by the difference in the magnitude of E for the matrix and inclusion appears upon deforming the two-phase ingot [6]. Our calculations showed that the mentioned additional pressure may exceed the external force by a factor of hundreds. The additional pressure can serve as the cause of ingot destruction during rolling [7].

In this study we investigated the influence of melt homogenization on the Young modulus and nanohardness of phase components of the Al–50% Sn ingot. The Al–Sn system has an eutectic-type phase diagram, while the Al–Sn alloys are characterized by the tendency to delamination into two phases—the solution of tin in aluminum and eutectic. The eutectic crystallizes at $t = 228.3°\mathrm{C}$ and content of Sn = 97.8 at % [8]. The microstructure of the Al–50% Sn alloy repre-

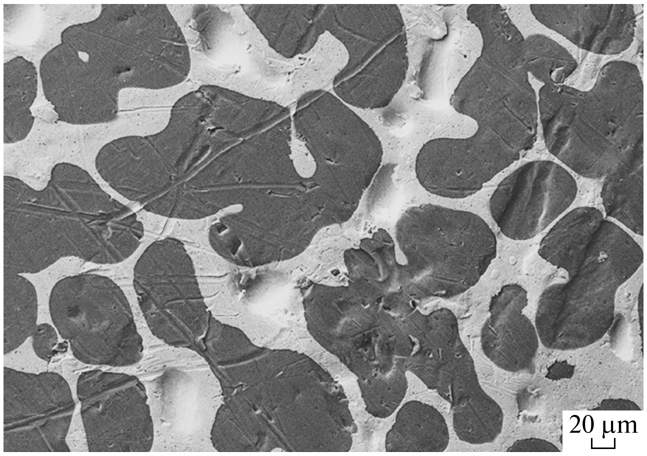

Fig. 1. Microstructure of the Al–50 wt % Sn alloy.

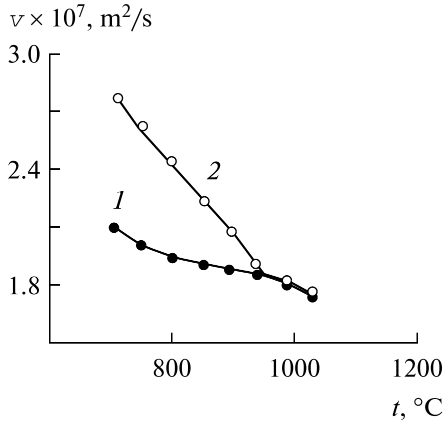

Fig. 2. Temperature dependences of the kinematic viscosity of the Al–50 wt % Sn melt [10]. (*1*) Heating and (*2*) cooling.

sents globular regions of the α solution surrounded by eutectic interlayers (Fig. 1).

The Al–50% Sn alloy is used in the production of titanium alloys as a foundry alloy, the use of which imposes its water-cooled rolling, which is often accompanied by the rejection of metal because of delamination along phase interfaces [9]. It was established previously [10] that the destruction of the microheterogeneous state of the Al–50% Sn alloy by means of its heating above the branching point of temperature dependences of its kinematic viscosity (950°C, Fig. 2) with the subsequent cooling and crystallization leads to the improvement of the ingot machinability by pressure and excludes the delamination of metal during rolling [9]. It was necessary to reveal how the melt homogenization affects the mechanical properties of separate components of the ingot—the solid solution of tin in aluminum and eutectic (see Fig. 1). The authors assumed that the delamination of the Al–50% Sn foundry alloy during rolling is the additional pressure caused by the difference in the Young moduli of the α solution and eutectic [8]. The destruction of microheterogeneity with the subsequent cooling and crystallization of metal determines the variations in the structure of the α solution and eutectics, which manifests itself in a variation in their elastic properties, primarily the magnitude of E.

EXPERIMENTAL

In this study, to evaluate the additional pressure caused by the difference in elasticity moduli of the α solution and eutectic, we measured the Young modulus of phase components of the Al–50% Sn ingot using the nanoindentation method. The measurements are performed for the samples fabricated by various methods: the traditional one at the heating temperature of liquid metal of 700°C and with melt homogenization by means of metal heating to 1150°C. We additionally investigated the influence of measurement of crystallization conditions of metal—an increase in the cooling rate of the sample by an order of magnitude. Measurements of the Young modulus and nanohardness were performed using a nanosclerometric module of an NTEGRA Probe nanolaboratory (NT-MDT, Zelenograd, Russia). In order to reveal the nature of the observed phenomenon, we also additionally investigated the crystal structure and elemental composition of phases of the samples by traditional methods of metallography using an Auriga CrossBeam workstation. A focused ion beam was used for sample preparation, energy-dispersive microanalysis (EDS) allowed to reveal the elemental composition of the phases, and the analysis of electron backscattered diffraction patterns (EBSD) allowed to investigate the crystal structure of metal in the experiments. Investigations were performed at the Ural Center of Shared Use “Modern nanotechnology” of the Institute of Natural Sciences of the Ural Federal University.

RESULTS AND DISCUSSION

The results of measurements are presented in the table. It is established that the homogenization of the metallic liquid affects the Young modulus of the Al–50% Sn alloy most strongly. We evaluated appearing mechanical stresses, which are caused by the two-phase state of the Al–50% Sn sample, or by the presence of the eutectic and α-Al. The calculation showed that the additional pressure, which is caused by the difference in elasticity moduli of the eutectic and α-Al, is lower for the homogenized sample than for the reference sample by a factor of 9; on the contrary, quenching increases the additional pressure by a factor of 6.5. Even the preliminary homogenization of the sample does not save the situation—an increase in pressure by a factor of 4.6 is observed. We assume that just the additional pressure, which is caused by the two-phase state of the Al–50% Sn sample, served as the cause of its destruction during rolling.

The investigation into the elemental composition of phases of the samples of the Al–50% Sn alloy, which were fabricated by different methods, revealed the presence of aluminum in the eutectic in amounts of 1 wt % (reference sample) and 0.5 wt % (sample homogenized in the liquid state). A combination of heating the liquid metal to 1150°C and increasing the cooling rate during crystallization by an order of magnitude gave no variations in the elemental composition of the eutectic. The α-Al phase of the sample with the titanium additive contains this element in the amount of 1 wt %, and no titanium was found in eutectic interlayers.

A comparative crystallographic analysis of the crystal structure of globular α-Al inclusions in the samples by the electron backscattering diffraction (EBSD) showed that they have a polycrystalline structure. Misorientation histograms of crystallites for the sample homogenized in the liquid state and a reference one are constructed (Fig. 3). Correlated misorientations reflect those between the neighboring points and uncorrelated misorientations reflect those between randomly selected points in the data set. The theoretical curve shows what we could expect from a random set of orientations. We can see that correlated (black) and uncorrelated (gray) misorientations strongly differ from the theoretical curve and from one another. The difference between uncorrelated misorientations and the theoretical curve appears mainly due to the strong texture. The texture is especially strongly expressed for the homogenized sample. The histogram of the correlated distribution for both crystallites indicates that the number of low-angle boundaries, i.e., the boundaries with a misorientation angle smaller than 15°, which are not seen in the uncorrelated distribution for the reference sample, is large. The analysis of histograms of misorientation angles for the reference sample and sample homogenized in the liquid state shows that numerous large-angle boundaries occur in the former case and almost all boundaries are low-angle in the second case; the degree of material texturing is larger for the homogenized sample. In both cases we deal with textured metal, which will obligatorily affect its elastic characteristics.

The Taylor factor maps for the system of deformations (slip system) typical for aluminum $\{111\}\langle -111\rangle$ with loading direction parallel to the OX axis were obtained as a result of the analysis of the Kikuchi diffraction patterns. The comparison of obtained Taylor maps showed that the sample homogenized in the liquid state is characterized by a higher degree of deformation uniformity.

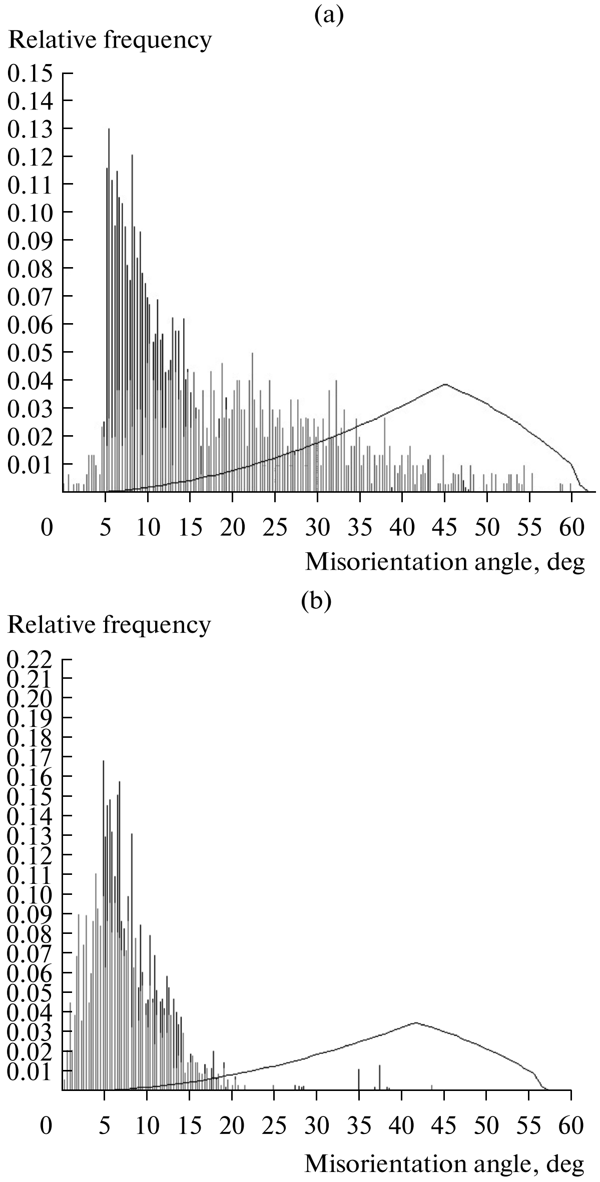

Fig. 3. Histograms of misorientation of crystallites for (a) reference sample and (b) sample homogenized in the liquid state. (a) Traditional method of sample fabrication—heating temperature of liquid metal $t_h = 700°C$ and cooling rate $v_{\text{cool}} = 0.2°C/s$. (b) $t_h = 1150°C$ and $v_{\text{cool}} = 0.2°C/s$. Correlated misorientations are black and uncorrelated ones are gray; the theoretical curve is presented.

Thus, the nanoindentation method allows us to experimentally measure the Young modulus of separate phases of metallic alloys, which opens up principally new possibilities for performing theoretical calculations and modeling the pressure-treatment conditions of metals.

Young modulus (E), the fraction of the elastic component of deformation (r), and nanohardness (NM) of the phases of the Al–50 wt % Sn alloy

Method of sample preparation		Solid solution of Sn in Al			Eutectic		
t_h, °C	v_{cool}, °C/s	r, %	E, GPa	HM, GPa	r, %	E, GPa	HM, GPa
700	0.2	3.3	68.88 ± 5.10	0.73 ± 0.07	–	97.93 ± 4.93	0.51 ± 0.06
1150	0.2	6.8	49.24 ± 3.01	0.62 ± 0.03	0.8	55.37 ± 1.81	0.52 ± 0.04
700	4.0	3.7	68.89 ± 1.10	0.66 ± 0.02	–	100.73 ± 4.9	0.56 ± 0.01
1150	4.0	7.6	36.56 ± 0.47	0.69 ± 0.03	2.3	45.22 ± 1.61	0.65 ± 0.02

CONCLUSIONS

(i) The influence of microheterogeneity and crystallization conditions of the Al–50 wt % Sn melt on the mechanical properties of phase components of the ingot—the Young modulus and nanohardness—is investigated. These indices are measured by the nanoindentation method.

(ii) It is established that the cause of delamination of the Al–50% Sn foundry alloy during rolling is additional pressure, which is caused by the difference in the Young moduli of the α solution and eutectic. The homogenization of the melt with the subsequent cooling and crystallization leads to changes in the structure of the α solution and eutectic, which manifests itself in varying their elastic properties, primarily the Young moduli. The evaluation of appearing mechanical stresses, which are caused by the two-phase state of the Al–50% Sn sample (the presence of the eutectic and α-Al), showed that the additional pressure for the homogenized sample is lower than that of the reference sample by a factor of 9; on the contrary, quenching increases the additional pressure by a factor of 6.5.

(iii) An additional investigation into the crystal structure and elemental composition of the phases of Al–50% Sn samples revealed that the variation in the Young modulus of the α solution is not associated with the variation in the elemental composition but is caused by the change in the crystal structure: the sample homogenized in the liquid state is characterized by a higher degree of uniformity of deformation, almost all boundaries are low-angle for it, and the degree of texturing of the material is higher.

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