Influence of the Structural State on Mechanical Behavior of Tin Babbit

F.A. Sadykov, N.P. Barykin, I.Sh. Valeev, and V.N. Danilenko

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Phase constituents of tin babbit have been specified by experimental methods. It has been established that β-phase exerts an influence on elongation, ultimate strength, yield strength, and other mechanical properties of the alloy. The significant distinction in deformation behavior between the cast alloy and the rolled one is attributed to processes of failure of cast structure, its recovery, and recrystallization.

Keywords fracture, mechanical properties, structural state, tin babbit, x-ray

1. Introduction

The tin babbit [Sb (10-12 wt.%), Cu (5-6 wt.%), Sn (rest)] is widely used for producing bushes of steam turbine sliding bearings.[1,2] Service properties of babbit considerably depend on its chemical composition and structural state.[3,4] Small ductility (~6% elongation) is one of the drawbacks of the tin babbit that negatively influences service properties of the alloy. Treatment of a material causes its structural changes and affects physical and mechanical properties.

The available literature data on babbit are rather contradictory. It is known that Sn-Sb-Cu alloy (tin babbit) can comprise the following phases: basic α-phase, β-phase (SnSb compound), η-phase (Cu_6Sn_5 compound), ε-phase (Cu_3Sn compound), γ-phase ($Cu_{31}Sn_8$ compound), and Cu_2Sb phase. As the literature indicates, babbit with a high amount of tin consists of three phases: α, β, and η,[5,6] or α, β, and ε.[7,8] Moreover, according to Ref. 8, the basic α-phase is in the form of solid solution of antimony and copper in tin, whereas according to Ref. 9, it is in the form of three-component eutectic. Thus, determination of phase constituents in tin babbit is quite critical.

The influence of a strain rate on mechanical properties of the cast tin babbit was shown in Ref. 10. In literature there are no data on mechanical properties in different structural states.

The present article deals with investigations of the structure and the influence of a structural state on mechanical properties of the tin babbit.

2. Experimental Details

Babbit of the chemical composition [Sb (10-12 wt.%), Cu (5-6 wt.%), Sn (rest)] was selected as an object of investigation. For forming different structural states, the cast babbit was cooled at different velocities. The obtained β-phase crystallite size was 50, 100, and 250 μm. Moreover, to obtain the structure of babbit with a β-phase grain size of 30 μm, some specimens were subjected to rolling at room temperature (RT). Rolling was performed for several passages with a total value of relative compression equal to ~80%.

Mechanical tests of cylindrical specimens with the gauge diameter $D = 5$ mm and the gauge length $L = 5D$ were conducted on an Instron dynamometer (Instron Corp., Canton, MA). Specimens were subjected to elongation at RT at different strain rates in the range $\xi = 10^{-4}$ to 10^{-2} s^{-1}. Moreover, cylindrical specimens, 10 mm in diameter and 15 mm in length, were subjected to compression on a Shenk dynamometer (Shenk GmbH, Germany). Compression was conducted at room temperature and strain rates of $\xi = 10^{-4}$ to 10^{-2} s^{-1}. Deformation relief was studied on polished specimens with a cross section of 5 × 2 mm. The strain rate sensitivity coefficient m was calculated by using the formula:[11]

$$m = \log \sigma_m / \log \xi \quad \text{(Eq 1)}$$

where σ_m is the maximum flow stress.

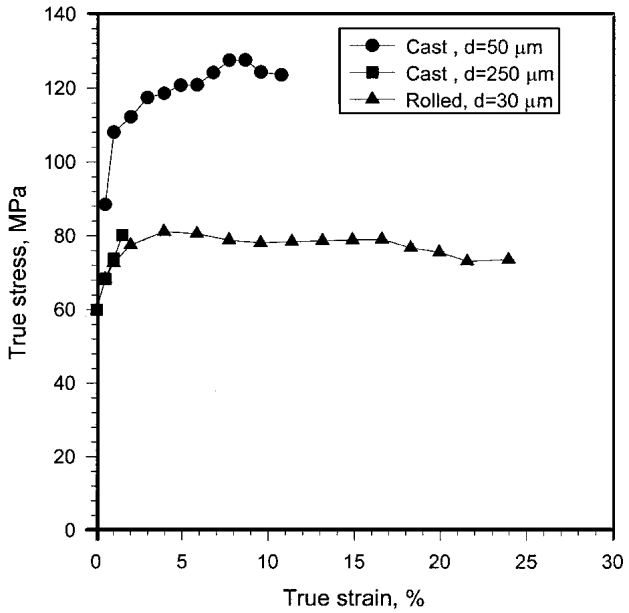

Fig. 1 True stress-true strain curves of babbit at different structural states at strain rate of 10^{-3} s^{-1}

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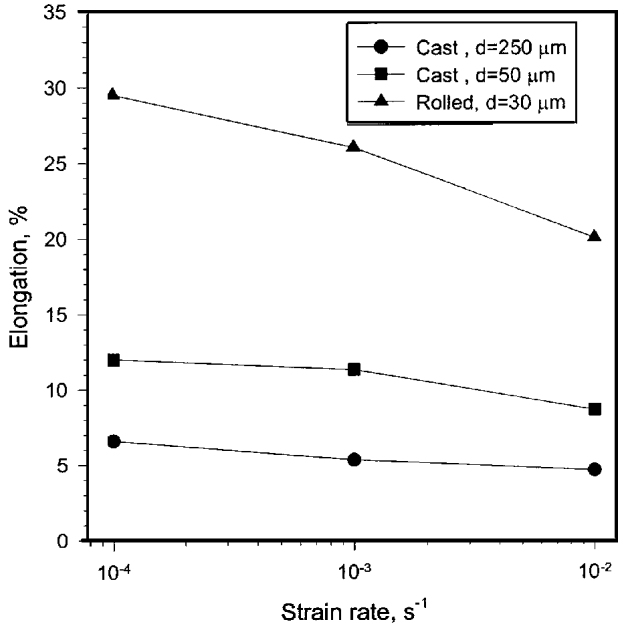

Fig. 2 Dependence of elongation of babbit on strain rate at different structural states

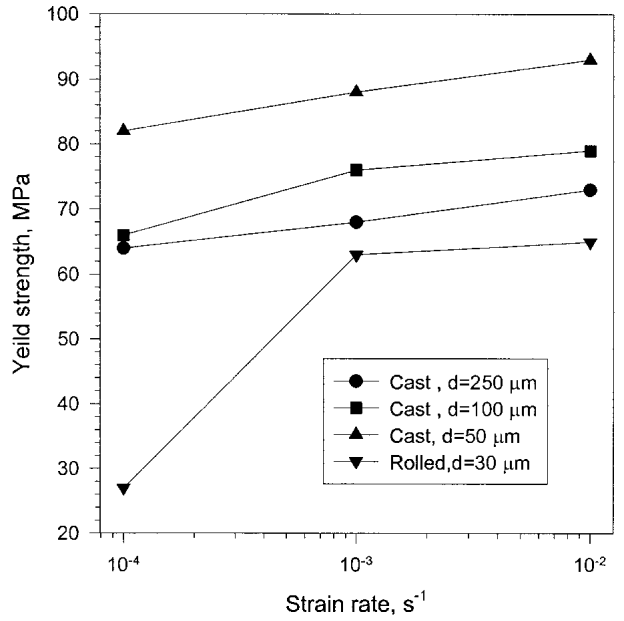

Fig. 3 Dependence of yield strength of babbit on strain rate

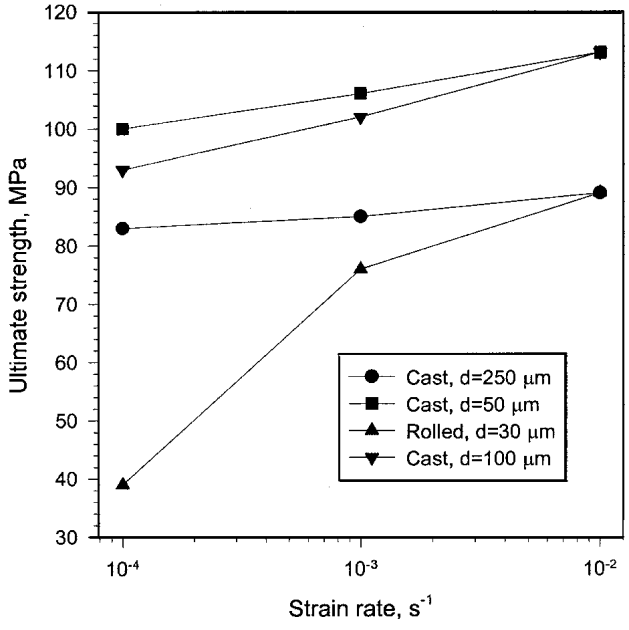

Fig. 4 Dependence of ultimate strength of babbit on strain rate

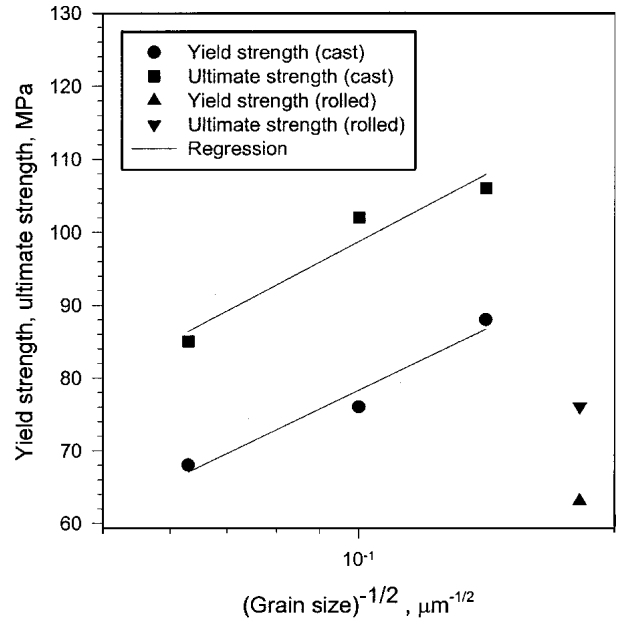

Fig. 5 Dependence of yield strength and ultimate strength of babbit on β-phase grain size

Microhardness was determined by means of a microhardness gauge under a load of 0.05-0.2 N. The load was chosen so that each print can find room on the surface of the expected η- or ε-phase. No less than 10-15 prints were made for each phase.

Optical (Neophot-32, Carl Zeiss Jena GmbH, Germany) and scanning electron (JSM 840, JEOL Corp., Tokyo) microscopes (SEM) were used to study the structure of the alloy. X-ray structure analyses were made by means of a diffractometer using Cu-Kα radiation and graphite crystal-monochromator.

Determination of the alloy's chemical composition was achieved by means of micro x-ray spectrum analysis by using a JXA-6400 analyzer (JEOL Corp.). An electronic probe ~1 μm in diameter was used for identification of phases.

3. Results and Discussion

The results of mechanical tests of specimens in various structural states are given in Fig. 1-5. The true strain-true stress

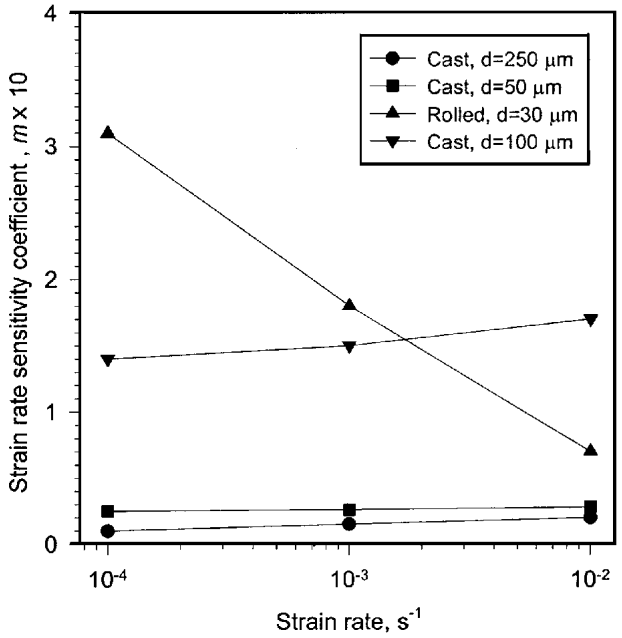

Fig. 6 Dependence of strain rate sensitivity coefficient of babbit on strain rate

Table 1 Cu_6Sn_5 Phase

hkl	2θ, Tabulated	2θ, Experimental	*d*, nm, Tabulated	*d*, nm, Experimental
101	30.24	30.44	0.2955	0.2936
110	43.18	43.09	0.2095	0.2099
102	43.42	43.25	0.2084	0.2092

Table 2 Cu_3Sn Phase

hkl	2θ, Tabulated	2θ, Experimental	*d*, nm, Tabulated	*d*, nm, Experimental
100	37.63	…	0.2390	…
002	41.82	41.75	0.2160	0.2163
101	43.27	43.25	0.2091	0.2092

curves of deformation of the alloy at different strain rates are shown in Fig. 1. There is a noticeable dependence of the flow stress on the grain size of β-phase. The decrease in the β-phase grain size from 250-50 μm for the cast alloy increases ductility and flow stress. For example, relative elongation increases from 5-12%, respectively. It should be noted that α-phase size is similar in cast alloys with different grain size, namely 50, 100, and 250 μm, and β-phase exerts an influence on ductility and other mechanical properties of the alloy. Moreover, rolling results in a significant increase in ductility of the alloy compared with the cast state. In particular, elongation of the rolled specimens was increased up to 26% and flow stress was decreased by 50-60% compared with the cast specimens with a β-phase grain size of 50 μm.

Figure 2 shows the dependence of elongation of babbit on strain rate. The view of curves indicates that for cast specimens

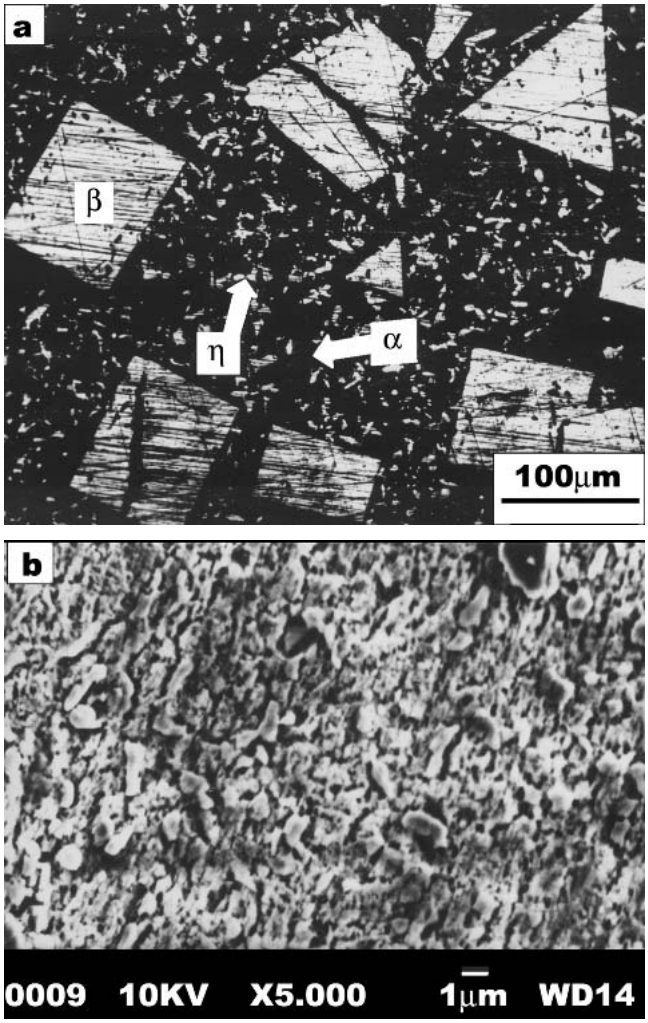

Fig. 7 **(a)** Microstructure of babbit in the initial state. The presence of α- (gray matrix, arrow), β- (big white crystals), and η- (little white crystals, arrow) phases. **(b)** View of α-phase.

there is no noticeable dependence of elongation on strain rate. However, for the rolled specimens the elongation increases from 20-30% with a decreasing strain rate from 10^{-2} to 10^{-4} s^{-1}.

The dependence of yield strength and ultimate strength on strain rate for the cast alloy is shown in Fig. 3 and 4, respectively. As illustrated, the dependence of yield strength and ultimate strength for the cast alloy is weaker than for the rolled alloy. The yield strength and ultimate strength are increased with decreasing β-phase grain size. However, for the rolled specimen the flow stress is less than for the cast alloy with the β-phase grain size of 50 μm.

Figure 5 shows the dependence of yield strength and ultimate strength on β-phase grain size. As illustrated, the decrease in the β-phase grain size increases both the yield strength and the ultimate strength according to the Hall-Petch dependence $\sigma = \sigma_0 + Kd^{-1/2}$ (where σ_0 is the initial flow stress and K is the coefficient). Moreover, the data on yield strength and ultimate strength for the cast alloy form straight lines with a similar slope. Consequently, the Hall-Petch dependence of flow stress on grain size is true for the cast alloy. On the basis of the

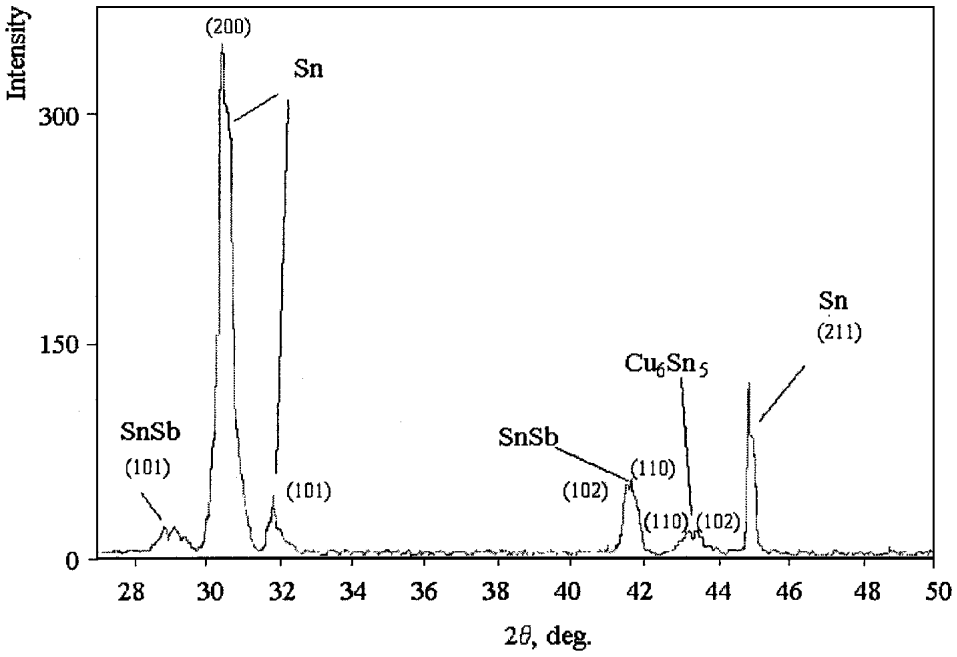

Fig. 8 X-ray analysis of babbit in as-cast state

Table 3 Data on Chemical Composition and Microhardness of Sn-Sb-Cu Babbit Phases

		Experimental Data				Literature and Calculation Data				
		Chemical Composition, wt.%				Chemical Composition, wt.%				
Phase Type	Expected Phase	Sn	Sb	Cu	Microhardness, MPa	Sn	Sb	Cu	Microhardness, MPa	Source
Matrix	α	88.1	11.6	0.3	220	96.6	3.4	0	230	Ref. 9
Macrocrystalline phase	β	56.6	43.1	0.3	950	49.4	50.6	0	970	Ref. 9
Phase in the form of "starlets" and "needles"	η	57.6	5.7	36.1	3200	68	0	32	3700	Ref. 9
	ε					38.6	0	61.4	5600	

curves, the σ_0 and K values were determined such that the dependencies of the yield strength and ultimate strength could be written in the form $\sigma_{0.2} = 61$ MPa + 256 MPa × $\mu m^{-1/2}$ × $d^{-1/2}$ $[\mu m]^{-1/2}$; $\sigma_b = 80$ MPa + 256 MPa × $\mu m^{-1/2}$ × $d^{-1/2}$ $[\mu m]^{-1/2}$.

Although the Hall-Petch dependence is true only for one-phase materials, its application in the presence of β-phase indicates a strong influence of the β-phase on mechanical properties of a material. In the given case, the main α-phase size was similar in different structural states of the alloy. Because the fractional volume of η-phase amount is small, it has a small effect on the mechanical properties of the material. The data on the rolled specimen do not fit linear dependencies of yield strength and ultimate strength on β-phase grain size. This is evidently connected with changes in structural states of other phase constituents of the alloy.

The data on the strain rate sensitivity coefficient m are given in Fig. 6. Note that the coefficient m for the cast alloy slightly depends on a strain rate and is 0.02-0.03, 0.01-0.02 and 0.14-0.17 for a β-phase grain size of 50, 250, and 100 μm, respectively. However, the alloy subjected to rolling displays rather high strain rate sensitivity; m values vary from 0.07-0.31 with a decreasing strain rate from 10^{-2} to 10^{-4} s^{-1}.

To explain the influence of the structural state of babbit on its rheological behavior, let us consider structural changes occurring during deformation of the alloy.

The tin babbit is a multiple-phase alloy consisting of three phases. Its microstructure in the as-delivered state is shown in Fig. 7. As illustrated (Fig. 7a), the structure of the alloy consists of α-phase (matrix), β-phase (large-scale crystals), and a small η-phase in the form of "starlets" and "needles." From Fig. 7b, one can see that the main α-phase (matrix) is a submicrocrystalline phase with a grain size of 0.5-1 μm. The size of β-phase is 100-200 μm.

For a more precise definition of the alloy's composition and phase constituents, the x-ray structure analysis of the alloy has been carried out. A fragment of the x-ray diffraction (XRD) pattern of the alloy in the casting state is shown in Fig. 8. Obviously, α- and β-phases are parts of the alloy. Diffraction maximums of the third phase are weaker than the first two phases.

Let us consider x-ray structural analysis data for the third phase. Table 1 shows the tabular and experimental data for the

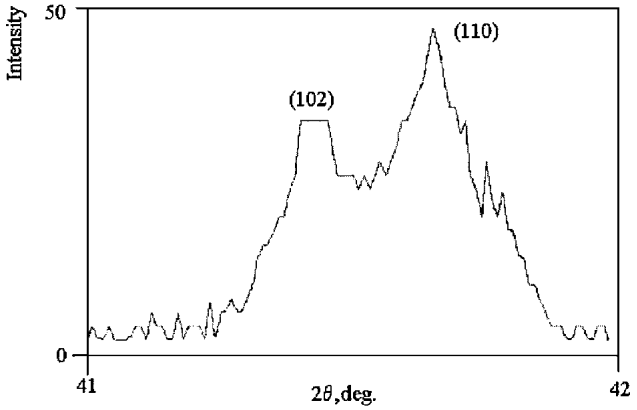

Fig. 9 Fragment of X-ray diffraction diagram at interval of 41-42° of babbit in as-cast state

Table 4 Cubic Phase

hkl	2θ, Tabulated	*d*, nm, Tabulated
002	29.13	0.3065
202	41.68	0.2167
222	51.64	0.1770
004	60.38	0.1533
204	68.43	0.1371

Table 5 Hexagonal Phase

hkl	2θ, Tabulated	2θ, Experimental	*d*, nm, Tabulated	*d*, nm, Experimental
101	29.11	29.10	0.3067	0.3068
102	41.50	41.43	0.2176	0.2180
110	41.78	41.65	0.2162	0.2168
003	51.20	51.20	0.1784	0.1784
201	51.70	51.63	0.1768	0.1770
202	60.34	60.55	0.1534	0.1529
113	68.14	68.10	0.1376	0.1377
211	68.60	68.44	0.1368	0.1371

Table 6 Rhombohedric Phase

hkl	2θ, Tabulated	2θ, Experimental	*d*, nm, Tabulated	*d*, nm, Experimental
100	29.14	29.10	0.3064	0.3068
014	41.42	41.43	0.2180	0.2180
110	41.94	41.65	0.2154	0.2168
006	50.99	51.20	0.1791	0.1784
022	51.89	51.63	0.1762	0.1770
204	60.42	60.55	0.1532	0.1529
116	68.09	68.10	0.1377	0.1377
212	68.83	68.44	0.1364	0.1371

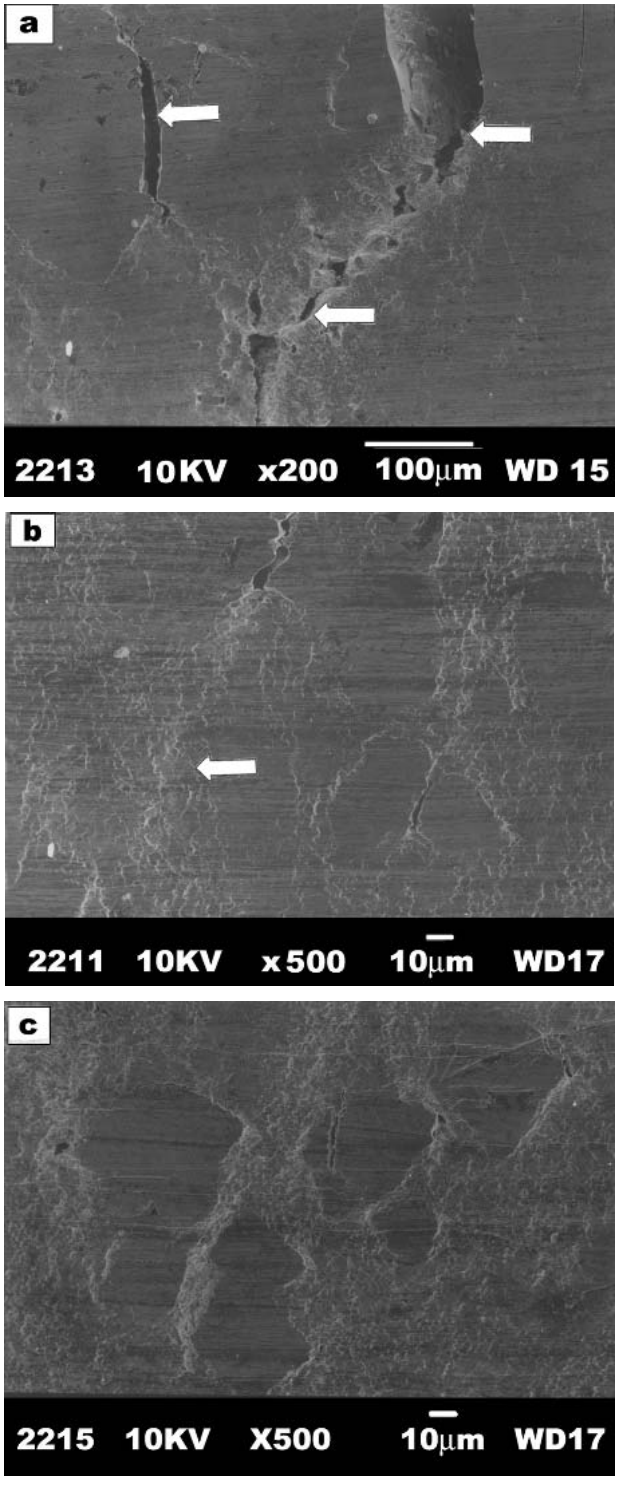

Fig. 10 Deformation surface of babbit with the different grain size of β-phase: **(a)** 250 μm; **(b)** 50 μm; **(c)** 30 μm (after rolling). Cracks are marked by arrows.

Cu_6Sn_5 phase. The comparison of experimental and tabular data for the Cu_3Sn phase is given in Table 2. In both cases the three most intensive maximums are used. For the Cu_3Sn phase, one of the maxima is not seen in the XRD pattern. Consequently, the amount of the Cu_6Sn_5 compound is rather small. It is confirmed by the data of chemical composition of this phase (Table 3).

It is known that β-phase belongs to a cubic syngony.[6,7] In

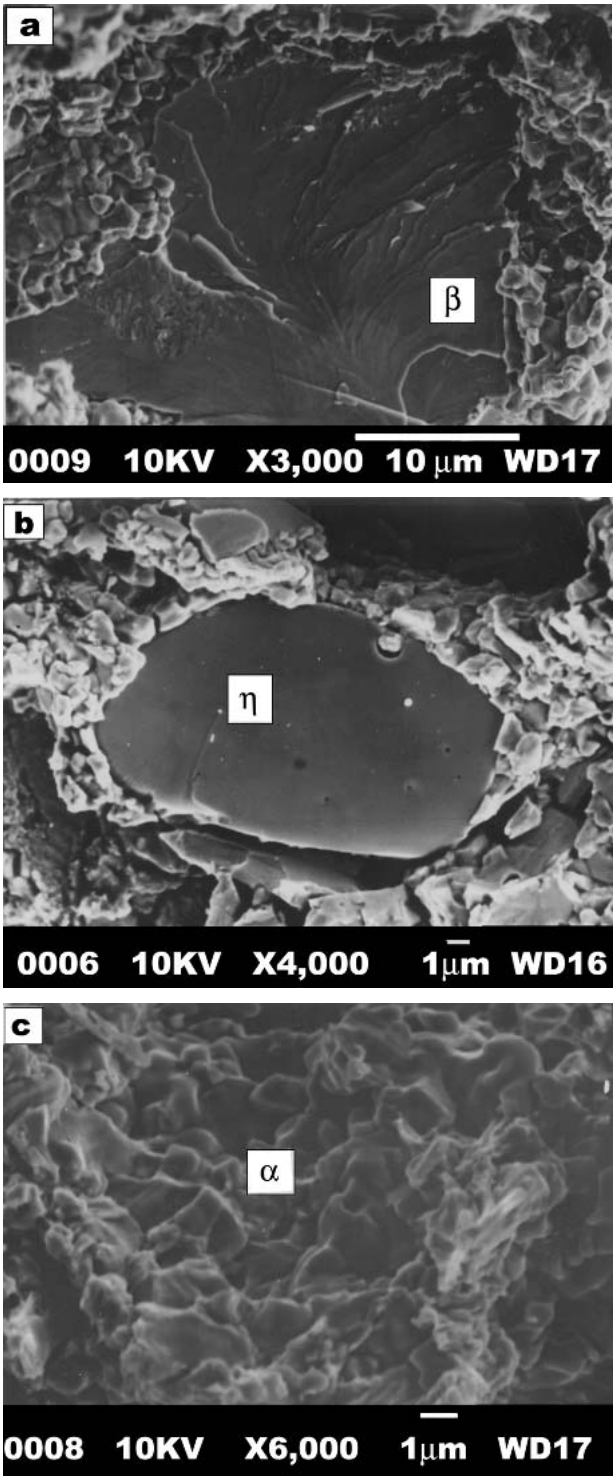

Fig. 11 Typical fractographs of babbit: **(a)** fragile fracture of β-phase; **(b)** fragile fracture of η-phase; **(c)** ductile fracture of α-phase (arrow)

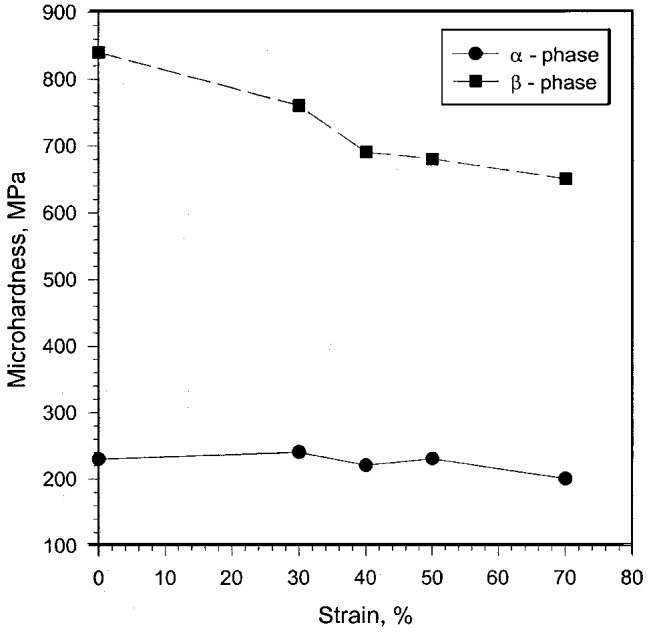

Fig. 12 Dependence of microhardness of α- and β-phases of babbit on rolling strain

this case, diffraction maxima shown in Table 4 should be observed on a diffractogram. The obtained experimental data are given in Table 5. The comparison of experimental data for β-phase with calculation data for the cubic syngony (Table 4) shows that additional diffraction maxima occur at Bregg angles $2\theta = 41$, 51, and 68°. As seen in Table 4, the cubic phase is characterized by the presence of one diffraction maximum at each angle.

For more precise definition of the experimental spectrum, these angles also were photographed (time of exposure was increased and scanning rate was decreased). The obtained data confirm the presence of two peaks in these angular intervals. The results for the angular interval 41-42° are presented in Fig. 9.

The presence of these diffraction maxima let us affirm that the β-phase of the alloy is not cubic. The obtained experimental data and the data on SnSb (lattice parameters: $a = 0.4326$ nm, $c = 0.5347$ nm) with hexagonal syngony received from the card index ICPDS-ASTM (33-118) are presented in Table 5. These data are in good agreement.

Note, however, that this is not the sole description of the received experimental data for the β-phase. There exist significant experimental difficulties connected with defining the crystal lattice symmetry of phases in this material because their reflections are coincident or very close. The obtained experimental data are compared with the calculation data for SnSb (which has a rhombohedral structure with $a = 0.4360$ nm period and the angle $\varphi = 59.20°$) in Table 6. These data agree as well.

However, the comparison of β-phase data presented in Tables 5 and 6 shows that the obtained experimental data are more suitable for hexagonal lattice than for rhombohedral syngony. Therefore, β-phase of such a babbit obviously has a hexagonal lattice.

Investigations of the deformation relief of the alloy were carried out after tension of specimens (relative elongation by 5% at a strain rate of 10^{-3} s^{-1}). Figure 10(a) shows that there are many cracks on the surface of the cast alloy with a β-phase

grain size of 250 μm. The cracks mainly initiate on matrix β-phase crystal interfaces, which was typical for many metals.[12,13] It should be noted that initiation of cracks in β-phase occurs only in some areas of the cast babbit surface. The inspection of the deformation relief of the cast babbit, with a β-phase grain size of 50 μm (Fig. 10b), shows that the number of cracks is less than in the previous case. It is also seen that the deformation relief of the matrix is more distinct. With regard to the rolled alloy, the inspection of its deformation surface shows that cracks are observed only in rare areas of the specimen's surface (Fig. 10c). It should be noted that matrix grain boundaries are clearly distinct.

The fracture study of broken surfaces was made by means of an electron microscope. Typical fractographs are shown in Fig. 11. The analysis indicates fragile fracture of β- and η-phases (Fig. 11a and b, respectively) and ductile fracture of the main α-phase (Fig. 11c). The low ductility of babbit is apparently conditioned by brittleness of the β-phase, which because of hexagonal lattice, has a limited number of slip planes available for plastic deformation. Moreover, the mechanism of fracture is also applicable to other materials with heterogeneous structure such as composites and intermetallics.[13,14]

The data on microhardness of α- and β-phases of the alloy after rolling with different degrees of compression are given in Fig. 12 and indicate the following. Microhardness of α-phase decreases slightly from 230 MPa (in the initial state) to 200

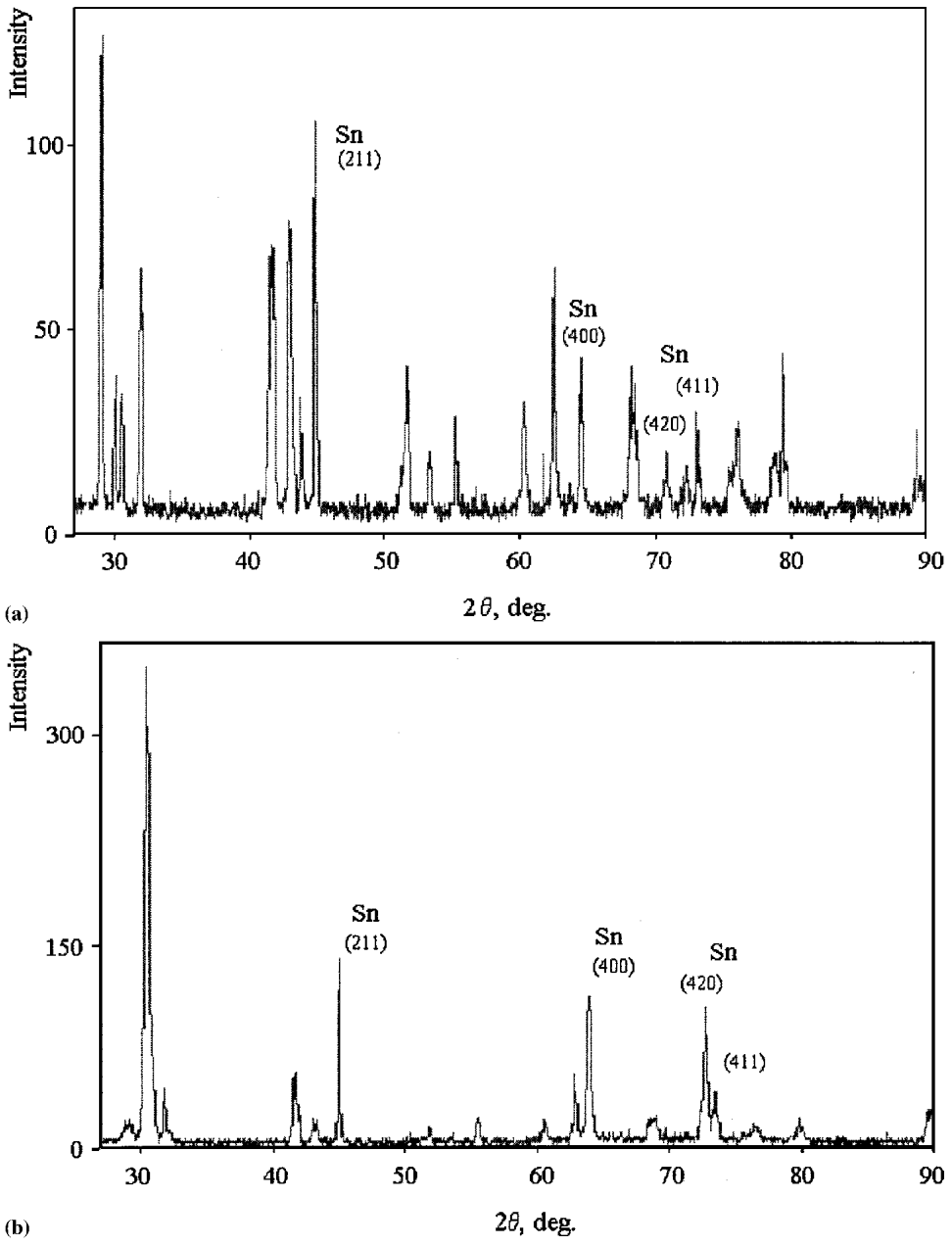

Fig. 13 X-ray diffraction diagrams of babbit in as-cast state **(a)** and after rolling **(b)**

MPa (in the state after rolling by 70%). However, the decrease in microhardness of β-phase is more significant (from 840-650 MPa).

The XRD pattern presented in Fig. 13 shows a decrease in a width of peaks of x-ray lines of the rolled babbit (Fig. 13a) as compared with the cast babbit (Fig. 13b). This explains softening and, perhaps, recrystallization of the α-phase of the alloy after rolling. In reality, the RT is the temperature of hot deformation for this alloy and is equal to $0.57 \cdot T_m$, where T_m is the temperature of melting of the main phase.

In general, ductility and other mechanical properties depend on α- and β-phases, because the amount of η-phase is small. When the size of α-phase is similar in different alloys (cast alloys with grain size of 50, 100, and 250 μm), the β-phase affects ductile and other mechanical properties of the alloy as a whole. The increase in β-phase grain size leads to the decrease in elongation of the alloy. After rolling, the recrystallization of α-phase occurs and ductility controls both the α- and β-phases.

A significant distinction in deformation behavior of the cast alloy from the rolled alloy can evidently be explained by processes of breaking the cast structure basis, recovery, and recrystallization of alloy phases after rolling, which significantly decreases flow stresses and increases ductility.

4. Conclusions

1) On the basis of full-scale investigations, it has been ascertained that cast high-tin Sn-Sb-Cu babbit consists of three phases: the α-phase of solid antimony and copper solution in tin with a submicrocrystalline grain size of 0.5-1 μm; the β-phase consisting of SnSb crystals with a hexagonal lattice; and a small η-phase (Cu_6Sn_5).
2) The decrease in the β-phase grain size from 250-50 μm for the cast babbit increases elongation from 5-12% and decreases flow stress. The strain rate sensitivity coefficient *m* is not noticeable and is 0.01-0.17.
3) Elongation of the rolled alloy is higher than for the cast babbit and is equal to 30%. The flow stress for the rolled alloy is 50-60% less than for the cast babbit. The strain rate sensitivity coefficient *m* for the rolled babbit is up to 0.31.
4) On the basis of fractographic study, it has been established that fragile fracture of β- and η-phases occurs, and ductile fracture of the main α-phase.

Acknowledgments

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