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The intermediate temperature ductility minimum α-tin bronzes

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In the paper the material parameters of the stain-hardening function have been determined, as well as the fractography of industrial bronzes, type UE7P and B6, after tensile tests within the temperature range 20÷500°C. It has been found that the strain-hardening exponent *n* of the function $\sigma = k\cdot\varepsilon^n$ and the strain-rate hardening exponent *m* of the function $\sigma_{(\varepsilon T)} = k\cdot\dot{\varepsilon}^m$ describe the changes in plastic deformation and cracking adequately and allow to determine the DMT of the investigated alloys explicitly. An analysis of fractography confirmed the substantial role of intercrystalline fracture as the effect of minimum plasticity of bronzes at elevated temperatures.

1. INTRODUCTION

In actual techniques of processing copper and its alloys, particularly tin bronzes, limited possibilities are encountered in the free shaping of these materials in industrial hot-working processes, due to the occurrence of intergranular brittleness. This determines a loss of ductility in these alloys at the intermediate temperature of deformation, the so-called ductility minimum temperature (DMT). The effect of DMT, a common property of many metals and alloys, like Cu, Ni, Ti, Fe, Mo, Ta and V, has been widely reported in literature [1-7], but its explanation is still controversial. It has also been found that some alloys do not display such an effect, depending on their chemical composition [8, 9] and in the case of ternary brass even a maximum of ductility could be detected at 675°C [10]. Investigations have shown that in the vicinity of DMT there are two essentially different deformation modes, at low and high deformation temperature, respectively, conditioning also two different mechanisms of fracture (Fig.1). These mechanisms can be described by the material parameters of the hardening function $\sigma = \sigma_0\cdot\varepsilon^n$, particularly by the coefficients *k* and *n* and the strain-rate hardening exponent *m* determined by tensile test basing on the relation $m = d\ln\sigma/d\ln(\dot{\varepsilon}/T)$ [11, 12]. The theoretical analysis permits to describe phenomenologically the deformation of metals and alloys within the DMT range in compliance with the relation:

$$\overline{\sigma} = K \mid \varepsilon^n + m\ln(\bar{\dot{\varepsilon}} / \bar{\dot{\varepsilon}}_0) \mid \quad (1)$$

where: - σ - effective stress

ε - actual strain until necking in the tensile-test sample

n – strain-hardering exponent
$\overline{\dot{\varepsilon}_0}$ - reference strain-rate

The presented constitutive law suggests that below DMT the mechanisms of plastic deformation and cracking are controlled by the first term of the equation, viz. changes of the work-hardening exponent *n*, whereas above this value they are dominated by the second term, mainly the parameter *m*. Thus an essential decrease of the value *n* and increase of the value *m* at intermediate temperature ought to condition a brittle intercrystalline fracture.

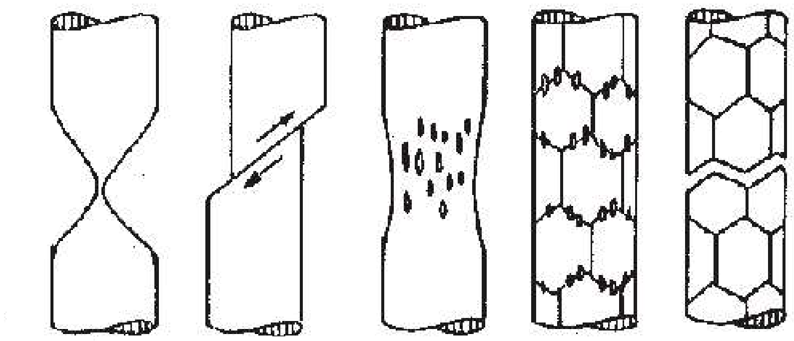

Fig. 1. Fracture mechanisms: (a) rupture due to necking, (b) rupture due to shear, (c) microvoids, (d) intergranular microvoids, (e) intergranular cleavage

The aim of these investigations is to determine the temperature dependence of the parameters of the work-hardening function of industrial tin bronzes with varying grain-sizes, subjected to tensile tests at elevated temperatures, as well as a fractographical verification of fractured samples from the viewpoint of the mechanisms of fracture in the DMT range.

2. EXPERIMENTAL PROCEDURE

Investigations have been carried out on α-tin bronzes type UE7P and B6 resulting from industrial smelting in Trefimetaux (France) and IMN (Institute of Non-Ferrous Metals) Gliwice. The chemical analyses of the materials used in the study are presented in Table 1.

Table 1. Chemical composition of the studied materials, wt. %

Bronze	**Sn**	**P**	**Bi**	**Pb**	**Sb**	**As**	**S**	**Fe**	**Zn**	**Ni**	**Cu**
UE7P	6,7	0,42	<0,01	<0,01	<0,01	<0,025	<0,001	0,018	0,046	-	Rem.
B6	6,75	0,15	0,0004	0,007	-	-	0,0024	0,007	0,039	0,003	Rem.

Details about the preparation have been reported elsewhere [5, 9]. High temperature tensile tests were conducted in the specimens by a 250kN machine (TTRMA 004) and a 100kN (4405) Instron type tensile testing machine in a dynamic argon and hydrogen atmosphere after remaining for 10 min at deformation temperatures in an infrared heating furnace. The heating rate to deformation temperature was about 100 K·min^{-1} and the strain-rates $\dot{\varepsilon}$ were in the range 1,2·10^{-3} s^{-1}÷ 6,0·10^{-2} s^{-1}. The deformation temperatures were 20°C to 500°C. The diameter of the tensile specimens was 6 mm, the gauge length 28 mm, and filleted radius 1 mm. The initial grain-size of the α-solution for tensile tests was about 500 μm and about 100 μm in the case of UE7P and B6 bronzes, respectively.

The material coefficients of the strain-hardening function *k* and *n* were determined basing on the strain hardening curves σ-ε and σ-φ making use of the following functions:

$$\sigma_p = k \cdot \varepsilon^n \quad (2)$$

$$\sigma_p = C \cdot \varphi^n \quad (3)$$

where: σ_p – actual stress calculated by means of the formula $\sigma_p = F_i/S_i$ [MPa]

ε - elongation of the sample determined basing on the formula $\varepsilon = (L\text{-}L_0)/L_0$ concerning the respective values of the actual stress after the calibration of the tensile-test machine

φ - logarithmic deformation calculated by means of the equation $\varphi = \ln(l_i/l_0)$

S_i – cross-section of the sample after its deformation, calculated basing on the constant volume of the measurement cylinder $l_i/l_0 = S_0/S_i$

F_i – load of the sample after its deformation read-off in the diagram

The constants *k* and *n* were determined analytically, making use of the linear regression function. The value of the plastifying stress σ at elevated temperature depends essentially on the strain rate. The influence of $\dot{\varepsilon}$ on the shape of the strain hardening curve is expressed by the modified Ludwig equation $\sigma = k \cdot \varepsilon^n \cdot \dot{\varepsilon}^m$ [14, 15]. As *m* depends essentially on temperature, but may also depend on the degree and rate of the strain, it is generally defined at a constant value of strain and temperature, as follows: $\sigma_{(\varepsilon,\,T)} = k \cdot \dot{\varepsilon}^m$ where $m = d\ln\sigma/d\ln\dot{\varepsilon}$. The parameter *m* was determined applying the method of stepwise changes of the tension rate of the samples within the range of (2÷100)mm/min. For comparison the parameter *m* was determined applying various relations described in [13].

Fractography was carried out on scanning electron microscopes type Cameca and JXA-50A (Jeol) at an acceleration voltage of 35kV and a magnification of 100 to 10000 times.

3. RESULTS AND DISCUSSION

In the investigated range of plastic deformation temperature (20-500)°C the changes of the value of the reduction of area at fracture (Z) and the parameters of the strain–hardening function *k, C, n* of the industrial bronze UE7P are similar (Fig. 2 and 3, Table 2). At room temperature the plasticity of bronze is high (Z ≈ 60%). To this corresponds the high value of the coefficient *n* (about 0,4 – 0,5) and *C*, *k* (about 600 MPa). In the DMT range (300÷500)°C the value of the reduction of area is small (Z<5%) and the values of *n* and *k*, *C* are on the level of about 0,04÷0,08 and (130-230) MPa, respectively. Approximate values of the strain-hardening exponent (about 0,4) in the temperature range (20÷200)°C indicate identical strain-hardening mechanisms of the alloy. Above 250°C the value of the exponent *n* changes radically, which proves a change of the mechanisms of plastic deformation and fracture. As the value of the strain-hardening exponent *n* contains essential data concerning the structure of the investigated material, the change of *n* characterizes adequately changes in the structure of the alloy under the investigated conditions of plastic strain. The coefficients *k* and *C* are of less importance in the analysis of srain-hardening. If treated as constants, they describe the given material within a limited range.

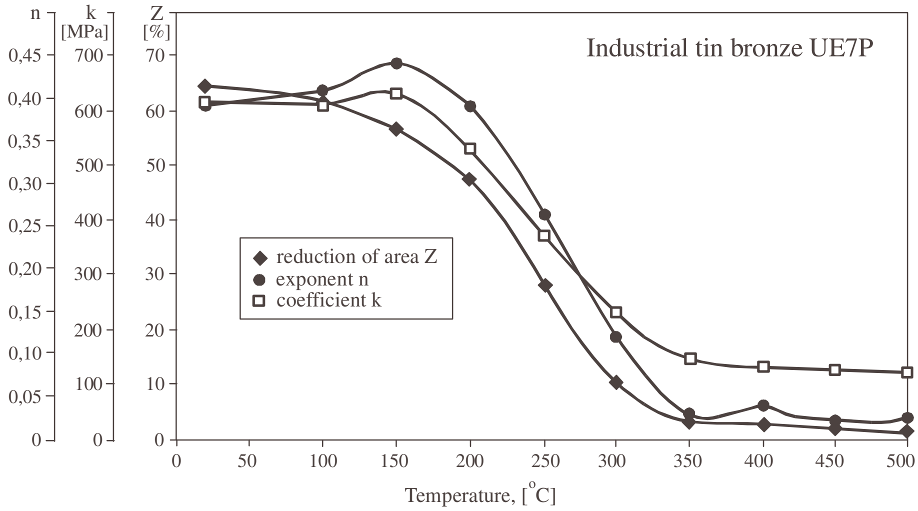

Fig. 2. Reduction of area at fracture (Z) and the exponents of strain-hardening *n* and strain-rate hardening *m* versus the temperature of tensile tests of industrial UE7P bronze

Table 2. Material parameters in the strain hardening function of UE7P bronze

Industrial bronze UE7P $\sigma_p = k \cdot \varepsilon^n$										
Temperature, °C	20	100	150	200	250	300	350	400	450	500
Reduction of area at fracture, Z [%]	58,8	59,4	58,8	35,3	19,7	8,9	2,48	3,3	-	1,6
Work-hardening coefficient *k*, MPa	628	612,7	612,6	530,5	320,6	228,9	131,6	130,7	130,2	129,7
Strain-hardening exponent *n*	0,44	0,41	0,42	0,39	0,21	0,12	0,03	0,04	0,02	0,03
Coefficient of correlation R	0,988	0,984	0,984	0,991	0,958	0,995	0,997	0,998	0,991	0,989
Industrial bronze B6 $\sigma_p = k \cdot \varepsilon^n$										
Reduction of area at fracture, Z [%]	77,8	69,5	-	63,1	36,2	30,3	41,3	48,0	55,4	52,8
Work-hardening coefficient *k*, MPa	740,1	753,8	-	801,9	685,1	556	474,7	319,9	-	151,2
Strain-hardening exponent *n*	0,31	0,34	-	0,37	0,32	0,27	0,22	0,146	-	0,05
Coefficient of correlation R	0,992	0,992	-	0,991	0,987	0,994	0,995	0,995	-	0,943

The graphic verification of the relation $\sigma_p = k \cdot \varepsilon^n$ concerning the analysed tensile curves of bronze B6 is to be seen in Fig.4, having taken into account the rigidity of the tensile-test machine. Calibration has thus made it possible to determine the extend of displacements in the same tensile test machine, taking into account the dynamic and kinematic properties of its whole driving and measuring system, providing a criterion of estimation of exact measurements and of the reliability of the obtained data. The linear course of the relation $\sigma_p(\varepsilon)$ in the logarithmic system permits to state that the strain-hardening curves of B6 bronze may be described in the investigated ranges of strain and temperature by the classical Ludwig equation [11, 14]. Changes of the exponent of this equation and of the reduction of area as a function of tensile temperature have been shown in Fig.5. It has been found that these values are quantitatively similar to the respective characteristics of UE7P bronze, although higher values of reduction of area in the temperature range (300÷500)°C indicate a more favorable effect of the grain-size refinement on the plasticity of this alloy. The values of the parameter *m* determined in the tensile test with stepwise changes of the strain-rate $\dot{\varepsilon}$ depending on the temperature of plastic deformation of the bronze B6 have been gathered in Fig. 6 and Table 3. It ought to be stressed that in the case of metals and alloys which react to the strain rate a change of the strain rate during the tensile test influences the value of the plastic resistance of the investigated alloy. This becomes particularly evident when the tensile test is carried out at elevated temperatures. Therefore the rigidity of the tensile test machine is of such importance. The low values of *m* at tensile temperature up to 300°C prove a small sensitivity of stresses to the strain rate in this range. If the tensile temperature is raised above 300°C, the parameter *m* increases evidently to about 0,2 at a temperature of (500÷600)°C. The diagram of the curves of *n* and *m* of the modified Ludwig equation [15] $\sigma = k \cdot \varepsilon^n \cdot \dot{\varepsilon}^m$ (Fig. 6) indicates distinctly that the temperature at the intersection of these curves (about 300°C) determines the ductility minimum temperature (DMT) or the so-called intermediate temperature of brittleness (ITB) [1], at which the material displays the highest brittleness.

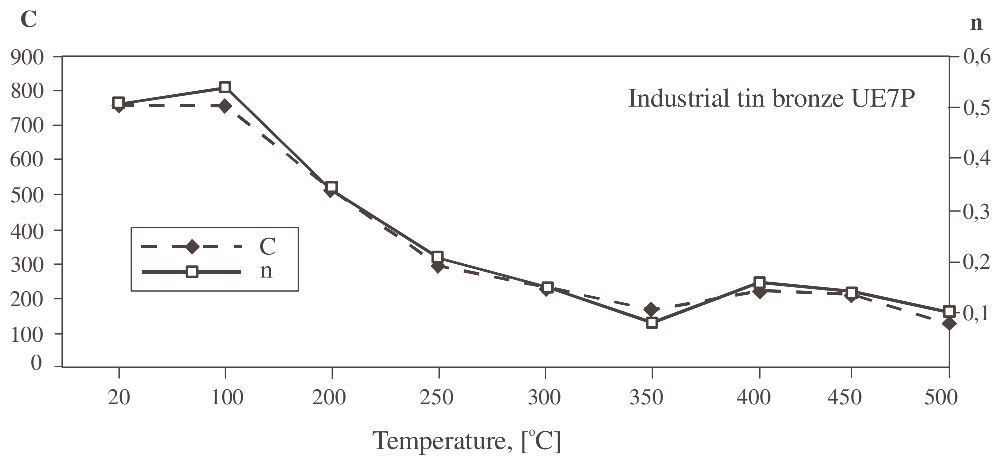

Fig. 3. The influence of the temperature of plastic deformation on changes of the coefficient *C* and the exponent *n* as a function of strain-hardening of industrial EU7P bronze

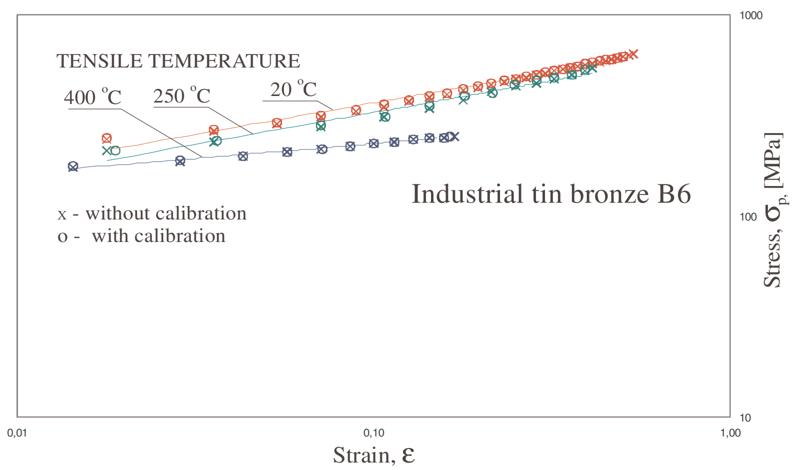

Fig. 4. Strain-hardening curves σ_p - ε of industrial B6 bronze on the logarithmic scale

Figs. 7 and 8 illustrate the electronic microfractographies of the investigated bronzes in the neighbourhood of DMT. Bronze UE7P with a grain-size of about 500µm displays up to 250°C a complete transcrystalline-ductile fracture. At 250°C i.e. just below DMT, a mixed brittle and transcrystalline-ductile fracture is to be observed with a considerable share of an intercrystalline surface (Fig. 7a). At DMT we have a typical intercrystalline-brittle fracture (Fig. 7b). Bronze B6 with a grain-size of about 100 µm displays at about 300°C a mixed fracture (Fig. 8a), whereas in the DMT-range (about 350°C) we get an intercrystalline-ductile fracture (Fig. 8b).

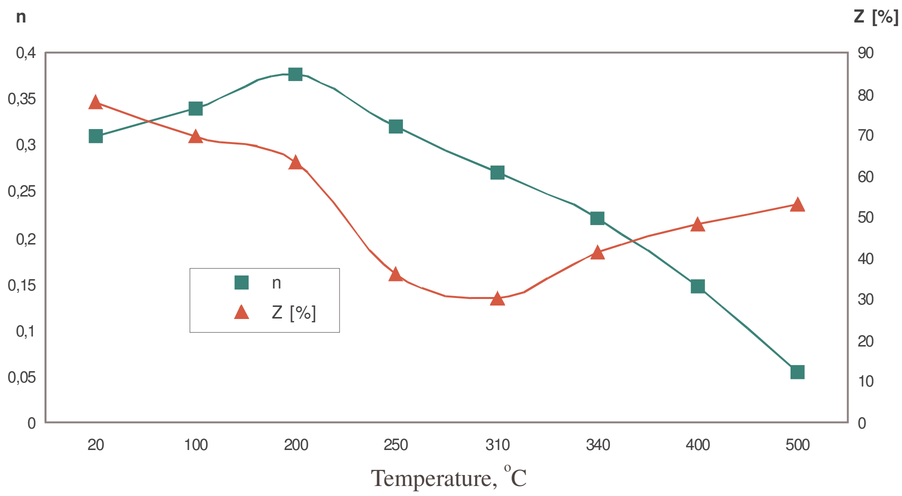

Fig. 5. Dependence of the reduction of area (Z) and the exponent of the strain-hardening *n* function on the temperature of plastic deformation of industrial B6 bronze

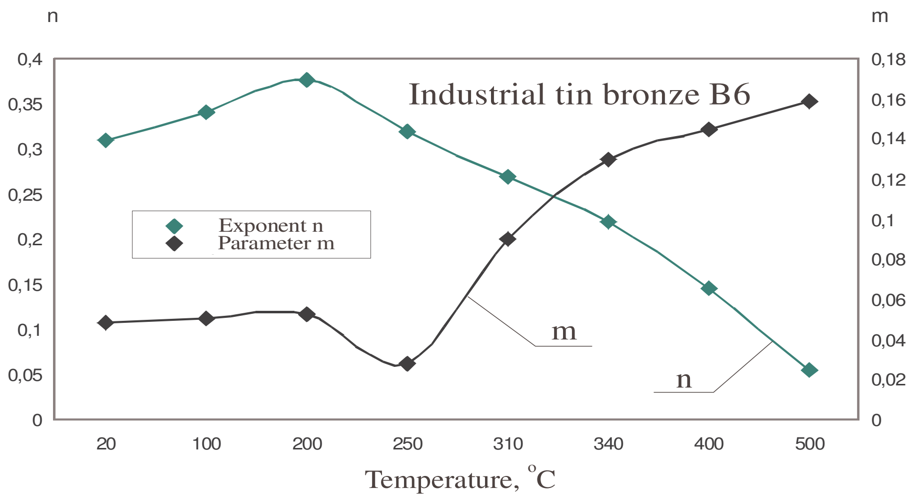

Fig. 6. The influence of the temperature of plastic deformation on changes of the strain-hardening exponent *n* and the parameter *m* of industrial B6 bronze

The investigated bronzes, deformed at above DMT, are characterized by the occurrence of a transcrystalline-ductile fracture. Fractographic analyses of the investigated bronzes confirm explicitly that the observed changes in the mechanism of fracture as a function of plastic strain temperature comply with the assumed phenomenological relation (1). Observations of fractures verify also precisely the determined DMT of these alloys.

Table 3. Values of the strain-rate hardening exponent of industrial bronze B6 deformed at elevated temperature

Industrial bronze B6 $\sigma_{(\varepsilon, T)} = k \cdot \varepsilon^m$											
Temperature, °C		20	100	150	200	250	300	350	400	450	500
Strain-rate sensitivity *m*	m_H	0,01	0,01	0,01	0,01	0,01	0,02	0,03	0,06	0,07	0,08
	m_C	0,06	0,05	0,07	0,06	0,05	0,12	0,14	0,17	0,18	0,18
	$\overline{m}$	0,04	0,03	0,04	0,04	0,03	0,08	0,12	0,14	0,17	0,17

m_H, m_C – the values of the strain-rate hardening exponent *m* calculated by means of Hedworth and Cutler equations, respectively [13], $\overline{m}$ - the average value

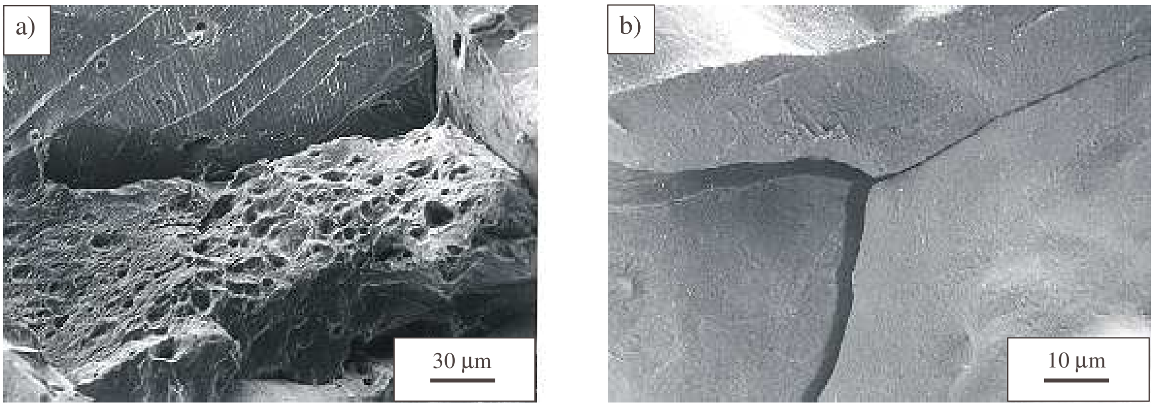

Fig. 7 Fractography of industrial bronze UE7P after tension at elevated temperature: (a) mixed fracture, 250°C, (b) intergranular fracture, 300°C

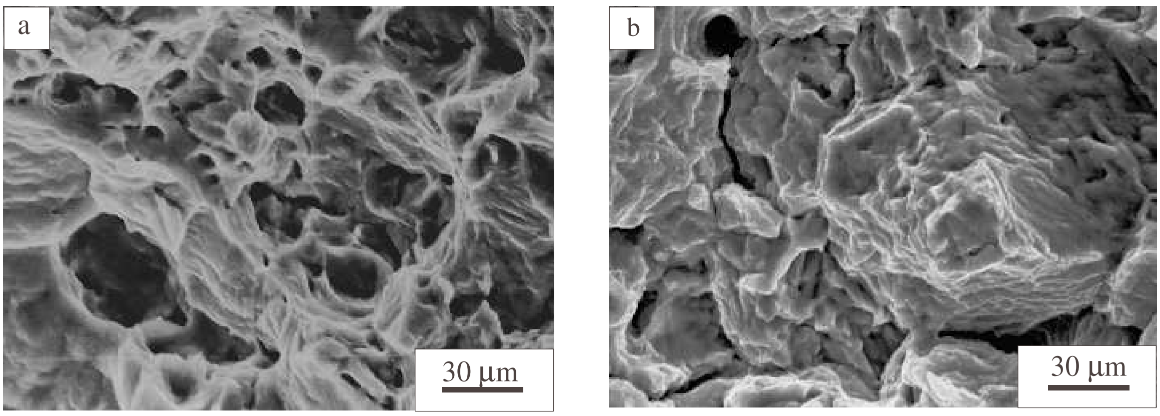

Fig. 8 Fractography of industrial bronze B6 after tension at elevated temperature: (a) mixed fracture, 310°C, (b) intergranular-ductile fracture, 350°C

4. CONCLUSIONS

The investigations discussed above have made it possible to formulate the following conclusions:

1. The parameters of the analyzed strain-hardening functions *k*, *C*, *n* for the bronzes UE7P and B6, deformed within the temperature range (20÷500)°C, display a similar course corresponding to changes of the reduction of area at fracture.
2. Taking into account the strain-rate in the analysis of plastisizing stresses at elevated temperatures it becomes possible to determine precisely the DMT of the investigated industrial tin bronzes.
3. The strain-rate hardening exponent *n* of the investigated tin bronzes changes with the temperature of tension from the average value of about 0,04 to about 0,18 at temperatures of 20°C and 500°C, respectively.
4. Fractographic investigations have confirmed qualitatively the temperature ranges of transcrystalline and intercrystalline fracture, expressed by the relation $\overline{\sigma} = K \mid \varepsilon^n + m \ln(\bar{\dot{\varepsilon}} / \bar{\dot{\varepsilon}}_0) \mid$.
5. An analysis of fractures confirms explicitly the influence of intergranular cracking on the minimum plasticity of the investigated bronzes in the course of hot working.

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