SECTION 1 PURE MATERIALS AND THE VACUUM TECHNOLOGIES

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STRUCTURE AND PROPERTIES OF DEFORMATED HIGH-PURITY Be

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The purpose of this study is to investigate the possibility of improving the mechanical properties and ductility of cast distilled beryllium sheets using plastic deformation and heat treatment.

By high temperature rolling with strictly controlled annealing received beryllium sheet with high mechanical characteristics. High temperature deformation of beryllium improves ductility in the sheet plane and in the transverse direction. Electron microscopic studies have shown that increasing the mechanical properties of beryllium connected with the formation during high temperature deformation of cellular substructure in sheets of beryllium.

As is known, the main disadvantage is the lowtemperature beryllium embrittlement. To improve the plastic properties of a metal of high purity is used combination with the creation of fine or subgrain structure. The ever-increasing requirements to the mechanical characteristics rolled beryllium require further study of the effect of deformation conditions and heat treatment of the material on its structure and properties [1-3].

Rolled sheets of cast beryllium have a number of advantages over the strong solid, but less ductile and highly textured sheets of metal powder [3]. They have a high resistance to crack propagation, better machinability and formability, provide higher quality welds. Due to a lesser extent textures compared with similar conditions rolled powder metal, sheets of cast beryllium have a higher ductility in the third direction (sheet thickness direction) and have the best performance in the bending test.

The purpose of most part of research beryllium rolled sheets is to get increased flexibility in the direction perpendicular to the plane of the sheet. As usual rolling, rolling in the two directions does not provide three-dimensional plasticity beryllium this leads to additional limitations in the application of sheet metal. In the U.S., published dozens of articles and reports that being sought the possibility of increasing the plasticity of sheets of beryllium in the third direction. Found, in particular, the low ductility beryllium sheet in the third direction connected with the formation of the deformation texture. [4]

Rolling conditions and properties of the sheet of beryllium determined grade and purity of the starting material. The higher content of impurities, the lower the permissible amount of compression and higher rolling temperature. Hot rolling of beryllium powder is performed at temperatures of 900 °C and above. The total reduction ratio reached 30:1.

Sheets are usually rolled in one direction with a small cross rolling. Mechanical properties of high temperature rolled sheets is usually 20-40% lower than the sheets after warm rolling. [5].

The average grain size in high temperature rolled sheet is higher than that after warm rolling, causing decrease of its mechanical properties.

Warm rolling of beryllium is generally carried out at temperatures of 650-790 °C. Usual, the number of passes 20-30, the total reduction (16-18): 1. To relieve stresses rolled sheets were annealed at 760 °C [5].

Chir and others [2] rolled bars of electrolytic beryllium 150x150x75 mm size first at 950-1050 °C to destroy macrocrystalline casting structure, and then at lower temperatures to prevent grain growth. It is noted that with increasing strain rate at a constant temperature, the intensity of the deformation texture is noticeably reduced. The large reduction per pass increases assorted material. Therefore it is recommended to use small reduction (<15%) and frequent heat of blanks.

In [6] beryllium bars size $280 \times 280 \times 380$ mmreceived by a method filling the bottom or centrifugal casting initially rolled at 1020 °C and then at 780 °C. Reduction per pass was 10-15%. After rolling with a total reduction of 85-90% stainless steel shell was removed and after rolled uncoated sheet to a thickness of 0,05-3,8 mm.

In [7] used a warm rolling castings. After preliminary deformation of billets at 600-800 °C with the total reduction of from 4:1 to 18:1 rolled sheet at a low temperature (250-600 °C). Because of the rapid hardening at low temperature rolling reduction quantity must not exceed 5-10% per pass. With a decrease in the rolling temperature and an increase in the degree of deformation of the average grain size in the annealed billets significantly reduced.

Structure sheets of substantially pure beryllium depends annealing conditions. Logerot [7] shows that after annealing warm rolled sheets of of electrolytic beryllium at 700-750 °C, the growth of grains is small, but when the rolling temperature of 950 °C, even short annealing leads to rapid grain growth. Therefore, after the rolled sheet was annealed at 750 °C for 1 hour and slowly (100 deg / h) was cooled to room temperature.

At optimum temperature increase rolling reduction ratio is usually accompanied by an increase in elongation and a decrease in the sheet plane of plasticity in a direction perpendicular to this plane. This texture effect is the result follows from the nature of the plastic deformation of monocrystals [8].

From the analysis of the published results on the effect of temperature on the properties of the rolling beryllium sheets that optimum deformation conditions are different for different types of metal. On the one hand, the rolling temperature decrease accompanied by improved strength characteristics by increasing of work hardening or decreasing the of the grain size after annealing. On the other hand, at low temperatures, increases the probability of formation of microcracks and reduced value of maximum permissible compression.

When comparing the mechanical properties of deformed materials must take into account the substructure factor - the nature of the formed dislocation substructure, which is critical to provide enhanced material properties. In [9, 10] found that the bending test more textured laminate sheet of beryllium in some cases have higher ductility. Electron microscopic studies have shown that this effect is not associated with the texture, but with a subgrain structure of the material. Formed in the process of plastic deformation and annealing smaller subgrains (1-10 microns) at sufficiently large angles relative orientation (3-5 °) play the role of common grains. The characteristic for the fully recrystallized state of the metal in the material destruction of transgranular with developed subgrain structure has changed in the grain. Consequently, the ductility of the material is determined not only by the amount involved in the deformation of the slip systems, but to a large extent ease of crack and the character of their distribution in the metal.

Effect of heat treatment on the kinetics of the second phase from the supersaturated solid solution and the mechanical properties of cast beryllium affects mainly in the high temperature deformation. The most detailed kinetics of the release of excess doses of cast beryllium deformed sheets studied in [11], which investigated the effect of annealing temperature and duration of hardened beryllium sheets on the nature of the second phase. Quenching temperature was 900 °C, aging was carried out in the range 500-780 °C. The growth rate of precipitates increases with increasing temperature. Oriented relative to the matrix of hexagonal plate FeBe₁₁ after 5 min. aging at 780 °C according to lose their orientation due to increased die sizes, while at a temperature of 650 °C, precipitate particles remain coherent with the matrix up to 10 hours incubation. Electron diffraction shows that the plane (111) of coherent particles, such that precede exudates AlFeBe₄ c face-centered cubic lattice, is parallel to the (0001) plane beryllium matrix. Annealing the samples for 15-30 minutes at 1000 °C does not lead to the complete dissolution of inclusions AlFeBe₄.

Levin and colleagues [12] studied release kinetics in the alloy Be-Fe, containing 0,95% Fe aging in the temperature range 400-500 °C. Low-temperature aging to promote homogeneity release particles FeBe11 (density of precipitates within the matrix particles was approximately the same as at the grain boundaries). Emissions do not exceed the size of 1000 Å. Test of samples in tension and compression at 20 °C after aging different modes showed that they have low plastic characteristics. The tensile elongation does not exceed 0.5%. Perhaps the low plasticity of samples tested is not connected with precipitates of the second phase of a supersaturated solid solution, as a consequence of the high rate of hardening of the samples. The aging process results in a significant change in the properties of the material as well as the grain boundaries and, therefore, must have some influence on the nature of the subsequent plastic deformation of the metal.

Effect of aging on the nature of the plastic deformation of raw beryllium and aged at temperatures 20-300 °C and Pointe Bastien studied [13]. The authors note that the feature of the pre-aged material is more uniform plastic deformation of the matrix material and intergranular fracture occurs at higher strains than in the case of the parent metal.

This paper consists of two parts: the first devoted to the influence of thermomechanical processing of distilled cast beryllium substructure and mechanical properties, the purpose of the second part of this paper is to study the effects of aging on the structure during the subsequent plastic deformation and mechanical properties of cast beryllium.

EXPERIMENTAL

In this work, we used vacuum melted beryllium into ingots rate of about 99.9%. The material composition specified in Table. 1.

Table 1

Impurities	Mn	Mg	Al	Cu	Fe	Ni	Cr	Si	Мо	0	С
Content	0,3	0,2	0,3	0,3	0,14	0,1	0,1	0,3	0,1	0,3	2

The impurity content in the studied beryllium (impurities, 10-2%)

In order to destroy the texture of casting and produce equiaxed small grain structure were subjected to deformation by extrusion ingots with a 3:1 compression and subsequent precipitate to its original size. After the recrystallization annealing, the grain size in blanks is 80 microns. These blanks were the starting point for subsequent rolling in combination with various circuits thermomechanical processing. To compare the results of the mechanical properties of rolled sheets prepared control samples on modes that are most commonly used for cast rolling distilled beryllium. Reduction per pass was 10-15% at the rolling temperature of 600 °C. The total reduction was 80%. After deformation recrystallization annealing carried out at 750 °C for 1 hour.

Mechanical test received samples were in tension

and bending. Tensile samples had a flat shape with a length of the working part 10 mm cross-section of about 4 mm 2. Samples flexural size $4 \times 1 \times 30$ mm were tested in three-point loading scheme. Bending radius of the blade was 2 mm and the distance between supports of 18 mm. Speed the movable gripping tensile testing machine and the bending knife the bending test was 0.2 mm/min. Structural studies were carried out by optical and electron microscopy.

Initial preform previously subjected to homogenization at 1000 $^{\circ}$ C for 1 hour, was rolled at a temperature of 870 $^{\circ}$ C. Dwell time between blank two

passes at this temperature is strictly controlled and changed with the increasing speed of heating the workpiece on the cross section. The samples were examined after 10 passages, which corresponded to 80% deformation.

Table 2 shows the mechanical test results of samples rolled at temperatures of 600 and 870 °C. It can be seen that the high temperature deformation promotes simultaneous increase strength and ductility characteristics of a tensile test and bending test.

Table 2

Rolling temperature, °C	Type of test								
		Tensic	on	Bending					
1	$\sigma_{\scriptscriptstyle B},g\!/mm^2$	$\sigma_{\rm T}, kg/mm^2$	δ, %	Ψ, %	$\sigma_{\scriptscriptstyle B},kg\!/mm^2$	$\sigma_{\rm T}, kg/mm^2$	α , grad		
600	32,1	24,7	5,2	4,3	90	36	32		
870	44,5	31,4	10,5	8,6	145	51	52		

The mechanical properties of the rolled beryllium

Yield strength σ_t a tensile test for samples rolled at a temperature of 870 °C, increased to 40% and the values of elongation δ and necking Ψ increased by 2 times.

As mentioned above, the increase in ductility of beryllium laminate in two directions in the plane of the sheet accompanied by a decrease in ductility in the "third" direction - transverse to the plane of the sheet due to the influence of the texture. Increasing the angle of bending is 60% after the high temperature rolling shows a simultaneous increase in the plasticity of the sheet plane and in a transverse direction.

After rolling, the grains stretched in the rolling direction, and inside them is a slight region of weak disorientation (Fig. 1).



Fig. 1. Structure beryllium after rolling at 850 °C. The total amount of deformation of 80%, x 115

Electron microscopic studies showed that the deformed grains are composed of sub-grains with a size of 3-4 microns large enough angles mutual disorientation, reaching 7-10 $^{\circ}$ or more (Fig. 2). For the substructure of the control samples, the rolling temperature of 600 $^{\circ}$ C, is characterized by a forest high dislocation density, and the walls of the cells or sub-grains are heavily blurred (Fig. 3).



Fig. 2. Substructure beryllium after rolling at a temperature of 870 °C. The total amount of deformation of 80%, x 13.000



Fig. 3. Substructure beryllium after rolling at 600 °C. The total amount of deformation of 80%, x 20000

Feature high rolling beryllium is that, after each compression and subsequent short time the material at a high temperature structural material state is located at the initial stages of the recrystallization process - the step of forming the cells [14]. Following the deformation of the high-temperature annealing leads to growth of cells or sub-grains while reducing the dislocation density inside them and increase their mutual misorientation angle. The boundaries between subgrains, misalignment of more than 3-5 °, become insurmountable for the glide dislocations and play a the

role of grain boundaries.

This is equivalent to the structural state of the ultrafine-grained material, and provides a high level of mechanical properties. Indeed, the most important structural sensitive characteristics of metals - σt yield strength, tensile stress σ r and the temperature brittleness Tx - depend on the grain size (subgrains, cells) and are associated with her well-known relations Hall-Petch and Petch-Stroh and Armstrong [8], which have form accordingly:

 $\sigma_{\rm T} = \sigma_{\rm ot} + k_{\rm T} d^{-S};$

 $\sigma_{r} - \sigma_{or} + k_{r} d^{-s}$, $\sigma_{p} = \sigma_{op} + k_{p} d^{-s}$; $T_{x} = A + B d^{-s}$, where σ_{or} , σ_{op} , k_{r} , k_{p} , A and B – are constant, and d – is grain size(subgrain).

The effect of increasing the mechanical properties of beryllium achieved by high temperature deformation can receive interleaved deformation at lower temperatures (500-600 °C), with high temperature shorttime annealing after each compression. Individual hightemperature annealing after the high degrees of deformation are ineffective and significant improvement of the mechanical properties, particularly ductility is omitted.



Fig. 4. Beryllium structure after rolling at 600 °C, x 560

Low-temperature deformation of beryllium (up to recrystallization temperature) form a honeycomb structure in the matrix of the "old" grain, but retains the "old" grain boundaries (Fig. 4), on which is free to spread crack, which originated in the material. Thus, although the material of the substructure, subjected to high temperature deformation or a combination of lowtemperature of deformation and annealing can be similar, the fracture behavior in both cases, is substantially different.

It should be noted an interesting feature of beryllium sheets produced by high temperature rolling. It was found that such sheets during subsequent exposure in the temperature range of 500-600 °C is practically not observed effect of aging related with allocation of impurities and decrease yield.

The cellular structure, which is formed in beryllium is characterized by a very large surface area boundaries, the latter being the most favorable places allocation of impurities. The high temperature deformation, accelerating the processes of diffusion, provide a redistribution of impurities with the formation precipitates at the cell boundaries. As a result, the impurity concentration in the matrix decreases. Therefore, an increase of plasticity observed in hotrolled samples except substructural factors associated with refining the matrix of impurities.

Let us consider further impact on the structure and properties of rolled beryllium various thermal treatments. Beryllium starting workpiece treated according to the modes described above, were homogenized at 1000 °C for 1 hour. Then, workpiece was annealed at 500 and 600 °C for 0.5-4, and 40 hours accordingly. After aging, deformation followed by rolling at a temperature of 500 °C. The total reduction was 80%. After rolling, the samples were calcined at 750 °C for 1 hour.

Table 3 shows the mechanical properties of the samples when tested in tensile strength at 20 °C, depending on the mode of aging prior to deformation and here are the mechanical properties of control samples, which processing modes described above.

Table 3

	Type of test								
Treatment		Tension	_	Bending					
	$\sigma_{\scriptscriptstyle B},kg/mm^2$	$\sigma_{\rm T}$, kg/mm ²	δ, %	Ψ, %	$\sigma_{\scriptscriptstyle B},kg/mm^2$	$\sigma_{\rm T}$, kg/mm ²	α, grad		
Test samples	32,1	24,7	5,2	4,3	90	36	32		
Aging 600°C, 0,5 hour	38,0	27,1	7,3	5,6	111	43	42		
Aging 600°C, 1 hour	-	-	-	-	94	38	30		
Aging 600°C, 4 hours	-	-	-	-	77	27	17		
Aging 500°C, 40 hours	41,0	29,7	8,5	7,6	121	55	48		

Effect of aging on the mechanical properties of the sheets of beryllium

You can note the great sensitivity of the investigated material to modes of aging, changes which significantly affects the mechanical properties, especially - on the plasticity.

For plastic deformation of beryllium characterized

by extreme heterogeneity, due to the large difference in shear stress in different crystallographic systems [8]. For example, the critical shear stress in the (1122) <1123>, and in the basal plane (0001) estimates differ by more than 2-3 orders of magnitude. The

heterogeneity of deformation of polycrystals leads to the formation of inhomogeneous substructures in a variety of grains, and after recrystallization - to inequigranular. As the deformation temperature increases specified anisotropy shear decreases in this way high temperature deformation should be preferred for an optimal substructure, and to improve the properties. But with an increase in temperature along with deformation effect of reducing shear stress anisotropy in the reverse direction operates the other two factors - the grain growth and intergranular slip. At high temperatures, stress slip deformation at the grain boundaries becomes lower than the shear stress for the secondary slip systems, resulting in some grains are weakly deformed, i.e. have a poorly developed substructure.

One of the possibilities of strengthening the grain boundary sliding and braking on the boundaries is impurity on the borders of secondary phases as a result of heat treatment. Kinetics of secondary phase from the supersaturated solid solution is that with increasing aging temperature impurity mainly formed on the grain boundaries.



Fig. 5. The substructure of the beryllium heat-treated before plastic deformation. Ageing 500 ° C, 40 hr, x 18,000

As seen from Table 3, the lower the aging temperature (500 °C, 40 h), prior deformation contributes to higher mechanical properties. Indeed, for the same amount of precipitated particles of impurities at low temperature aging, a higher density of them. Therefore, reducing the temperature aging while hardening the grain boundaries, leading to greater refinement of the matrix from impurities, facilitating its plastic deformation.

Plastic deformation of beryllium with a prehardened boundaries leads to a more homogeneous deformation in the bulk material. Average microhardness values in samples subjected to aging immediately after deformation was 15% higher than the control samples. In this variation of the measured values microhardness substantially lower.

Plastic deformation of the heat-treated material reduces the grain size after recrystallization annealing to 17 microns compared to 28 microns for the test samples. It is obvious that one of the reasons for the increase mechanical properties of the samples heat treated before deformation, is to reduce the average grain size. As the results of the performed study, the effect of heat treatment on the structure and substructure of beryllium in the subsequent plastic deformation mainly depends

on the size of the precipitated particles of impurities from the solid solution. Increase in the duration aging time at 600 ° C up to 4:00, not only removes the effect of improving mechanical properties, but leads to a strong embrittlement of samples after deformation. The bending angle is reduced to 17° versus 32° for the control sample. Increase in size of precipitated impurity particles also leads to a decrease in vield. With increasing aging time of samples at 600 °C from 1 to 4 hours it coagulates and precipitates growth. Structural studies show that in matrix of these samples are precipitates having a size of several microns. The study of influence on the degree of dispersion of precipitates strength characteristics showed that the yield is inversely proportional to the square root of the distance between the particles. This result is in good agreement with the model proposed in [15], in which the yield strength of the material connected with dislocation loops around the particles of precipitation. Coagulation and growth of the second phase in the aged material leads to weakening of the grain boundaries and at the subsequent plastic deformation greatly increased dislocation density near major emissions in the matrix (Fig. 6) and therefore the rate of hardening in this material is high. Furthermore, the large particles in the matrix can generate new dislocations due to the difference in specific volumes of the matrix and precipitated particles. The interaction of moving dislocations with the stress fields created by the large particles and causes a more rapid hardening of the material during plastic deformation.



Fig. 6. Substructure beryllium after aging 600 °C,
4 hour and subsequent plastic deformation. The total amount of deformation of 15%. 10.000 x

CONCLUSIONS

1. Thermomechanical processing distilled cast beryllium, consisting in alternating high temperature plastic deformation and annealing increases the strength characteristics of the material by 40% and plasticity 2 times. The effect of increasing the mechanical properties of beryllium after thermomechanical processing is to form the metal honeycomb substructure andin contrast to other types of deformation processing beryllium promotes dimensional plasticity.

2. A significant increase in ductility of beryllium after thermomechanical treatment, except substructural grinding achieved through additional refining matrix of impurities as a result of aging.

3. Plastic deformation of the pre-heat-treated

beryllium blanks leads to a significant increase in the strength and plastic properties simultaneously in three directions.

4. Improved mechanical properties of the heattreated beryllium before deformation due to the stronger and more uniform grain refinement in the sample compared with the test samples.

5. The greatest effect of thermal pre-treatment is achieved by using low temperature aging. The optimum size of the second phase corresponding to the maximum effect of the heat treatment is in the region 1500-2000 Å. A further increase in size of precipitates promotes embrittlement of the material.

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СТРУКТУРА И СВОЙСТВА ДЕФОРМИРОВАННОГО БЕРИЛЛИЯ ВЫСОКОЙ ЧИСТОТЫ

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Приведены результаты изучения возможности улучшения механических свойств и пластичности листов из литого дистиллированного бериллия путем использования пластической деформации и термообработки.

СТРУКТУРА І ВЛАСТИВОСТІ ДЕФОРМОВАНОГО БЕРИЛІЮ ВИСОКОЇ ЧИСТОТИ

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Наведено результати вивчення можливості поліпшення механічних властивостей і пластичності листів з литого дистильованого берилію шляхом використання пластичної деформації і термообробки.