EFFECT OF HIGH PRESSURE ON PORE FORMATION

B. V. Voitsekhovskii and B. I. Mikhailov

A method of formation of duralumin plates from the melt under conditions of hydrostatic pressure is investigated. The mechanism of the action of high pressure on the structure of the metal during crystallization is discussed. Results from the measurement of density, strength, and specific electrical resistance are presented.

A serious drawback of the known method of preparing plates from a duralumin roll sheet is the presence of intermetallic inclusions, holes, and residual stresses in the plates.

In the present work a simple and effective method of preparing plates is used; it involves crushing the melt together with the mold containing it. The mold (Fig. 1) is made in the form of a steel ring 1 and a steel backing 2. Before pouring the melt into the ring the mold is heated to the temperature of the melt. On crushing, the metal, contained inside the ring between the cold dies 3, cools rapidly, crystallizes, and congeals to the required temperature. The pressure developed in the melt during crushing can be determined from the formula

$$p = \frac{4F}{\pi D^2} - \frac{4\delta}{D}\sigma \qquad (1)$$

where F is the pressing force, D, δ are respectively the diameter and thickness of the ring, and σ is the yield point of the material of the ring.

For $F = 3 \cdot 10^5$ kg, $D = 10$ cm, $\delta = 0.25$ cm, $\sigma = 4 \cdot 10^3$ kgf/cm^2 the pressure, obtained from formula (1), is $p = 3500$ atm. In view of the small withdrawal of the melt in the formation of thin plates by this method, a material of any required composition and high physical and chemical purity can be used as the original material.

The pores in a metal obtained by the ordinary method appear mainly due to emanation of gas during solidification of the melt and due to its shrinkage.

According to the ideas set forth in [1] the process of crystallization of the melt under pressure can be considered to occur in the following way.

During the crushing of the mold with the melt the crystallization has a directed nature; it starts from the surface of the cold dies with the formation of primary dendrites. Both crystallization fronts extend into the depth of the metal toward each other. The shrinkage occurring here is freely made up by liquid metal; the decrease in the volume of the liquid metal is automatically compensated for by making the dies come closer by the required amount. In course of time the initial dendrites of each front expand and join each other. By this time the shrinkage can be made up by the metal penetrating into the shrinkage cavities along narrow interdendrite channels. But this is not always possible in view of the presence of surface forces that obstruct the flow of the liquid metal. The existence of surface forces can be accounted for by the formation of foreign film on the walls of the channel, which is nonwettable by the melt;
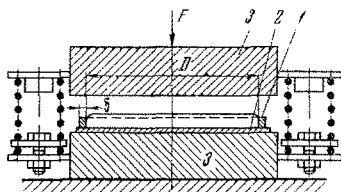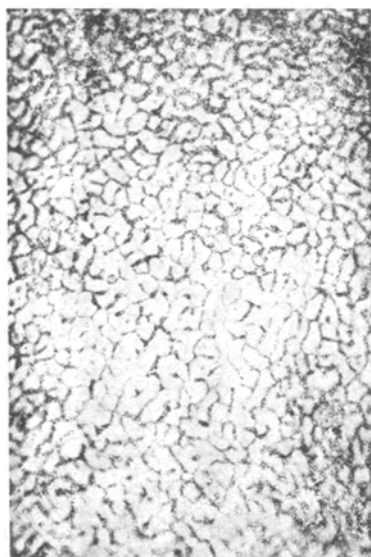

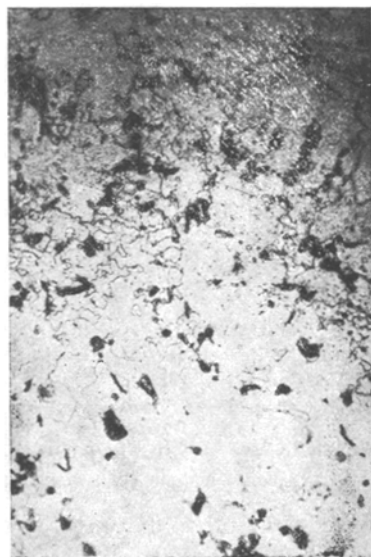
Fig. 1

Fig. 2   Fig. 3

this film may consist of, for example, products of interaction of the metal with the evolved gases. If the excess pressure in the liquid phase is insufficient for overcoming the forces of surface tension, viscosity, back-pressure of the gases in the cavity, etc., then intercrystal cavities are not filled and remain in the metal in the form of pores. On the other hand, if the necessary pressure drop always occurs, then as the crystallization front moves toward the liquid phase the newly formed intercrystal cavities will be filled by the liquid metal.

The liquid metal, flowing along the channel inside a pore, crystallizes partly on its walls, as a result of which the cross section of the channel decreases. Its transmission capability will remain nonzero until the surface-tension forces compensate for the pressing force from the excess pressure completely. Under the assumption of complete nonwettability of the channel walls by the metal, the diameter at which it gets blocked is given by the formula

$$d = \frac{4\alpha}{p} \tag{2}$$

where α is the surface-tension coefficient.

As the process develops, the dendrites growing from the opposite dies toward each other join and enclose the part of the pressing stress. As a result the excess pressure in the liquid phase decreases. For a further filling of the shrinkage cavities it is necessary that the pressure p, determined from formula (1), be larger than the ultimate strength of the formed plate.

It is obvious from formula (2) that the larger the pressure p of the melt, the longer the flow of the melt through the channel lasts. For p =3500 atm, α =700 dyn/cm [2], the blocking of the channel occurs when its diameter decreases to 0.01μ. Besides, with the increase in the pressure drop the velocity of the liquid metal $v \sim \sqrt{p}$ in the channel increases. Hence the time required for filling a hole decreases correspondingly. Thus an increase of the pressure in the liquid phase leads to a more complete filling of the shrinkage cavities, as a result of which their sizes decrease.

Gas holes appear due to the presence of a dissolved gas in the liquid metal. According to [3] gases extracted from aluminum and its alloys consist mainly of hydrogen. From the available data [4] hydrogen comprises 78% of the total volume of the gases absorbed by melted aluminum at 1200°C. This is explained by the small size of the hydrogen atom [5], which permits it to diffuse into the metal even at room temperature.

Since the solubility of hydrogen in aluminum decreases with the cooling of the melt, being in excess it must escape out from the melt. The process of gas emanation occurs in the entire volume of the melt with the formation of gas bubbles inside. Due to the increase of ductility of the melt on cooling and appearance of growing crystals, a part of these bubbles does not escape and forms gas holes inside the cast.

At constant temperature Sieverts' relation [6, 7] must hold between the solubility S of hydrogen and its pressure p in a gas bubble:

$$S = k\sqrt{p}$$

where k is a constant that depends on the temperature and the properties of the metal. On the other hand the pressure p inside the gas bubble is completely determined by the external conditions [8], i.e., by the pressure p_a of the external medium on the surface of the melt, the hydrostatic pressure p_2, and the pressure $2\alpha/r$ determined by the surface tension α at the gas−metal boundary and the radius r of the initial bubble.

Under the condition

$$(S/k)^2 < p_a + p_2 + 2\alpha/r$$

gas emanation does not occur.

The most intense gas emanation is observed during hardening of the melt, since the solubility of hydrogen in aluminum is greatly reduced. For example, for aluminum saturated by hydrogen from the atmosphere, at atmospheric pressure it decreases from $S_1 = 0.69$ cm^3/100 g in liquid state to $S_2 = 0.036$ cm^3/100 g in solid state [9]. But it should be remarked that the solubility of hydrogen in aluminum in other conditions can be substantially different from the values given above. Thus it is known [10] that hydrogen obtained in the reaction of aluminum with water vapor is dissolved considerably more easily than that obtained in the dissociation of molecular hydrogen.

An increase of the pressure on the melt during crystallization to a value at which the solubility of hydrogen in solid state increases to a value corresponding to its content in the melt leads to a complete suppression [11] of the process of gas emanation. Furthermore, the high external pressure compresses the holes in the metal, making it still more dense.

In the present work grade D16 duralumin in the form of hot−rolled bar is used as the initial material. The microstructure of the metal crystallized under a pressure p =3500 atm in the equipment described at the beginning of the article is shown in Fig. 2. It differs from the initial microstructure (Fig. 3); it has finer grains, and there are no holes inside the metal (amplification 300). As a result the density of the obtained metal increases compared to that of the original metal by 3.3%, i.e., from $\rho_1 = 2.687$ g/cm^3 to $\rho_2 = 2.776$ g/cm^3, as shown by measurements made with an accuracy of $\pm 0.25\%$. The x-ray analysis did not show any changes in the crystallographic structure of the metal.

A chemical analysis of the original metal and the metal obtained after crystallization under pressure, which was done to determine the difference in the contents of individual components (Cu, Fe, Si, Mg, etc.), showed that the composition is the same within the limits of the errors of measurements. The error in the measurement of the copper and iron components, which have the most pronounced effect on the density of the alloy, comprises $\pm 0.08\%$ and $\pm 0.01\%$ respectively. The variations in the density of the alloy due to these variations in copper and iron content should not exceed $\pm 0.2\%$. This gives a basis for the assumption that the 3.3% increase in the density of the metal crystallized under pressure is due to the decrease of its porosity.

Mechanical tests of the obtained metal show that its strength is the same as that of the original forged duralumin and it has an ultimate strength of 30 ± 2 kg/mm^2, which is 25–30% higher than the strength of annealed duralumin of the same grade.

It is found from measurements that the specific electrical resistance is 10–12% higher than in the case of the original forged metal and comprises $6.35 \pm 0.1 \cdot 10^{-6}$ $\Omega \cdot$ cm. This can be accounted for by the difference in their microstructures. In the original metal (Fig. 3) the impurities occur in the form of isolated coarse inclusions. In the metal obtained after crystallization under pressure the impurities are concentrated along the boundaries of the grains in the form of seams which insulate the grains from each other. Therefore the resistance offered to an electric current is higher.

If the metal crystallized under pressure is subjected to further forging, one can apparently expect an increase in the electrical conductivity and the mechanical strength.

Thus a high pressure applied to the melt during crystallization inhibits the process of hole formation and creates conditions for obtaining dense and strong metal.

LITERATURE CITED

1. V. M. Plyatskii, Stamping from Liquid Metal [in Russian], Mashinostroenie, Moscow–Leningrad (1964).
2. V. K. Semenchenko, Surface Phenomena in Metals and Alloys [in Russian], Gostekhizdat, Moscow (1957).
3. N. A. Galaktionova, Hydrogen in Metals [in Russian], Metallurgiya, Moscow (1967).
4. N. V. Okromeshko, Casting, Forging, and Thermal Processing [in Russian], Oborongiz, Moscow (1947).
5. B. A. Kolachev, Hydrogen Brittleness of Nonferrous Metals [in Russian], Metallurgiya, Moscow (1966).
6. A. Sieverts, Die Aufnahme von Gasen durch Metalle, Z. Metallkunde, 21, No. 2, 37 (1929).
7. K. Smittells, Gases and Metals [in Russian], Metallurgizdat, Moscow–Leningrad (1970).
8. L. I. Sokol'skaya, Gases in Light Metals [in Russian], Metallurgizdat, Moscow (1959).
9. C. E. Ransley and H. Neufeld, "Solubility of hydrogen in liquid and solid aluminum," J. Inst. Metals, Paper No. 1138 (1948).
10. W. R. Opie and N. J. Grant, "Effect of hydrogen on mechanical properties of some aluminum alloys," Foundry, 78, No. 10, 104 (1950).
11. A. G. Spasskii, Fundamentals of Cast Preparation [in Russian], Metallurgizdat, Moscow (1950).