The prospective technology of production of metal materials grains with extra high rate of solidification

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Abstract. This paper presents results of research of influence of extra high speeds of aluminum alloys grain solidification on the increase of mechanical strength characteristics of produced grains and semifinished products, which are made of grains by pressing. During the research it was determined that the most influential factor on metal grain and alloys solidification speed is the vapor film forming around the graining drop of liquid alloy. The vapor film forms due to transformation of the boundary layer into vapor state. The term ‘vapor barrier’ around graining object is implemented for the first time. The article offers the methods of removing the vapor barrier with an aim of a considerable increase of heat rejection intensity and, as a result, increase of grain solidification speed. It is determined that the only effective method of vapor barrier removal is a considerable increase of initial drop movement speed in the cooling liquid during the spinning of metal liquid alloy. The conducted experiment proved theoretical suppositions. The received semifinished products of grained aluminum alloys had a considerable upgrade of metal strength characteristics.

1. Introduction
The method of alloys peculiarities improvement by alloying has almost depleted its possibilities in respect to usual conditions of production of semifinished products of lingots. One of the prospective directions of metal and alloys quality improvement is granulating, which is based on usage of high rate of solidification of liquid alloy [1].

The essence of influence of rate of solidification on structure and peculiarities of multicomponent alloys results in creation on thin internal grain structure. In case of aluminum and low-alloyed alloys on its base, the crucial influence on the peculiarities is rended by the grain size. And in case of high alloyed aluminum alloys the peculiarities of the moulded state generally depend on the size of dendrite branches and the grade of development of dendrite porosity. The alteration of cooling-down speed of liquid phase before the beginning of crystallization and the speed of the mere process provide the fine crushing of internal grain driven by decrease of thickness of separate dendrite branches and the increase of quantity of these branches [2].

As the internal structure changes, the incrusting matters of second phase and internal micropores inevitably crush and allocate in a more uniformal way. The result of this process is a considerable inhance of mechanical peculiarities of the material.

Therefore, a purpose of this work is to explore the influence of extra high rate of solidification to aluminum alloys peculiarities improvement.
2. Materials and Experimental Methods

As the result of possibility of receiving a high rate of solidification, simplicity of machines and technology of production, the axifugal method of grain moulding received high popularity [3].

The method consists in the following: inside the rotatory sputter pour melted metal which under the effect of centrifugal force crushes into drops which are thrown through the holes in the cylindrical walls of sputter into the cooling-down liquid (water) [4].

It is important that during this method of grain moulding the cooling-down of drops which is occurring in water, provides reaching a considerably high speed of cooling-down of liquid-alloy drops, which accounts for \(10^6\) °C in a second for 1.0 mm diameter grains. Speaking about alloys of system Al-Cu-Mg the structure of grains, which are received by this method, is acutely crushed comparing with the structure of ingot of same composition. It is known that the presence of chrome, manganese, zirconium in high-duty alloys produce a positive effect on the complex of semiproducts mechanical peculiarities. It rises the temperature of alloy recrystallization, which facilitates the maintenance of effect of extrusion after the semiproducts thermohardening. High rate of solidification while grain moulding allows to receive abnormally supersaturated solid solutions. When the content of zirconium in the alloy is 0.4 – 0.8%, the initial intermetallics with zirconium are not present in the grain structure. The zirconium in this case is in the supersaturated solid solution. While heating before the thermal treatment and in the process of plastic deformation the supersaturated solid solution decays with the segregation of internal phase containing zirconium, which provokes lattice distortion. On a certain stage of the decay the hardening effect reaches the maximum value.

The conducted experiment aimed at increase of the grain solidification rate by the joint action of water eddy and cooling-down in the water solutions of substances which increase the water steam formation. 5-10% water solutions of alkali-metal chlorides (NaCl) and oxides of alkaline metals were used in the capacity of such substances. The transition from laminar to turbulent flow of the cooling-down liquid was produced with the application of swirlers. The conducted experiments showed the highest efficiency of such act in relation to increase of grain solidification rate.

The production of grains of alloys of system Al-Cu-Mg was accomplished by the axifugal method on a special laboratory facility [5].

The conceptual scheme of installation is represented on figure 1.

The installation for centrifugal spraying of grains consists of bell jar 1, which is at the same time bell jar for hardening tank, where the cooling liquid enters (service water) 2. The hardening tank has external rotative upper shell in the center 3 and internal rotative ladle 4, which receives the liquid metal alloy through a hole in the upper part 5. The rotation of external rotative upper shell 3 and internal rotative ladle 4 is synchronized. Due to centrifugal forces fusil metal is squeezed into the holes of internal ladle and passing through the holes of external moveable ladle, the metal gets into hardening medium.

It is known that when the speed of rotation of a water-logged body exceeds 3000 r/min, just as for the current facility, water is thrown aside due to the forming of airflow and water swirl, there appears air medium layer between the surface of rotative separating nozzle of the ladle and the surface of cooling liquid swirl. Due to the facility design it is possible to reduce to minimum the liquid alloy drop flight line in the air medium and, as a result, to keep the liquid alloy drops temperature at the moment of contact with cooling liquid equal to the temperature of liquid alloy in the casting mold, which favours the increase of graining speed. Cooling down in water, the grains get down to the bottom of external bell jar and discharge with service water through the inlet branch 6 in the bottom part of the facility. The electric engine 8 through the system of trucks and sockets provides the rotation of external nozzle of the ladle 3 and internal perforated ladle 4 with target speed.
Figure 1. The conceptual scheme of facility for production of grains with extra high speeds of solidification [5].

The detailed description of facility concept is represented in [5]. The speed of liquid alloy ladle rotation is conceptually important, because it defines the requested travel speed of the dripping, which provides the vapor barrier removal around the crystalizing grain.

The rinsing and diffusion of grains into fractions were carried out according to traditional for metal power industry methodics. Nevertheless, while drying of grains the hot airflow drying on vibro-dryer conveyer was applied. It was done with an aim of decreasing the oxidation of grain surface due to the presence of water vapor while slow drying.

The grains had homogeneous grain fineness and the diameter of about 1.0 mm. The prime yield after the grain moulding accounted for 90 %. The calculation showed the speed of grain cooling-down at this method of solidification. The received grains further on were prepared for metal forming. The heating was up to the temperature of 420 °C, the time of heating \( \tau \) accounted for 8 hours. Then the grains were exposed to hot compressing with the production of a bar, a rolled section. The compressing was conducted in the laboratory fitting out on the fluid-actuated press by the force of 6000 kN with the extrusion ration \( \lambda = 20 \div 30 \). The item endurance was conducted from the temperature of 480–500 °C and with the following artificial aging at the temperature of 190 °C during 8 hours.

3. Results and Discussion

The conducted research of structure and mechanical peculiarities of received granulated materials confirmed the theoretical assumptions. A considerable increase of alloy mechanical peculiarities was determined at the increase of grain solidification rate.

It is determined that the main difficulty on the way of increase of 1.0 mm grain crystallization speed is the forming of vapor barrier, which appears due to the convey of heat from crystallizing object to border layers of cooling liquid. As soon as the temperature of nearby water layers exceeds the temperature of boiling, appears the vapor barrier. Due to low heat conduction of vapor, the transition of heat from cooling down grain lowers sharply. The experiment proved that for the removal of vapor barrier it is required that the initial speed of liquid alloy drop was high enough at the moment of its entering into cooling water. The initial speed of grain movement is determined on the basis of lack of time for transition of required quantity of heat, which is needed for transforming the nearby water layers into vapor the volume of which does not exceed 1% of grain volume.

Overall, the speed of initial drop movement in the liquid alloy depends on metal liquid alloy physical peculiarities, ladle geometrical parameters and cooling liquid parameters. Also it was theoretically determined and experimentally proved that the needed initial drop speed depends directly on the drop radius, metal alloy thickness, ratio of drop heat dissipation to environment, temperature lapse (the difference of crystallizing drop temperature and cooling liquid temperature) and depends in inverse proportion on liquid alloy drop (grain) mass, volume vapor medium mass, cooling medium
vaporization heat capacity, cooling medium heat capacity, temperature lapse between cooling medium vaporization temperature and its operational temperature.

At the determined initial grain speed the calculated grain cooling temperature achieves the speed of cooling of flakes which have a considerably smaller thickness than grains. The cooling speed of flakes (small flat sheets of abnormal form and small thickness) is under \(10^8\) °C/sec at their crystallization on copper backing (copper platforms) [1]. But because of their small thickness it is rather hard to conduct further pelleting and pressing of semifinished parts of produced flakes. It is a serious barrier on the way of industrial application of technology of production of moulded piece of flakes. It is determined that the sizes of particles may be regulated within determined limits during the centrifugal sputtering of liquid alloy. In case of sputtering and cooling down of liquid alloy by gas the speed of cooling down is lower when the particles size is equal, than at centrifugal diffusion into water. Nevertheless, the method of sputtering allows to receive the particles of a less size and due to this to come up to the speeds of cooling which are achieved at alloy diffusion into water. However, the industrial application of this technology faces the same problem as at pelleting and pressing of semifinished parts of flakes [3].

Overall the presented technology of aluminum alloy grains production by centrifugal separation applying the removal of vapor barrier is the unique graining technology which provides the grain target size with a high speed of their crystallization and makes its industrial application possible.

In the context of alloys of system Al-Cu-Mg it is determined the increase of mechanical properties of semifinished rods received by the granulating technology. Table 1 shows mechanical properties of alloys AA2017 and AA2024 in the delivered state \(T_1\) (heat-treated and not naturally aged) of pressed samples, received by traditional technology of pressing bars of ingots (1), pressing of grains, received without the removal of vapor barrier at grain crystallization (2) and according to presented technology (3).

### Table 1. Mechanical properties of pressed semifinished parts of aluminum alloys of system Al-Cu-Mg received by different technologies (1, 2 or 3).

| Alloy  | Production technology | Resistance to rupture, MPag | Yield offset, MPag | Percentage extension, % | Reference |
|--------|-----------------------|-----------------------------|-------------------|-------------------------|-----------|
| AA2024 | Pressing of ingot (1)  | 450                         | 400               | 16                      | [6]       |
| AA2024 | Pressing of grains (2) | 559–566                     | 419–436           | 13.9–15.7               | [1]       |
| AA2024 | Pressing of grains (3) | 620–625                     | 460–468           | 9.1–10.5                | our data |
| AA2017 | Pressing of ingot (1)  | 410                         | 250               | 15                      | [6]       |
| AA2017 | Pressing of grains (2) | 546                         | 355               | 17.5                    | [1]       |
| AA2017 | Pressing of grains (3) | 582–584                     | 390–398           | 11.4–12.8               | our data |

**4. Conclusion**

The presented technology allows to produce high-strength aluminum grains of high quality, which are further used as semifinished raw part at production of parts by pressing, hot die forging or baking (after obligatory previous pelleting).

By this means, basing on the theoretical and instrumental research it is possible to evaluate good perspectives of the elaborated technology. The conducted technical-economic study showed that at a very insignificant cost increase of the semiproducts production and items of alloys of system Al-Cu-Mg
it is possible to increase the strength characteristics of granulated materials by 15 – 18 % in relation to earlier observed high-strength aluminum alloys.

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