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STRUCTURE AND MECHANICAL PROPERTIES OF VERTICAL UPWARDS CONTINUOUSLY CASTED ALUMINIUM WIRES

STRUKTURA I MEHANIČKE OSOBINE VERTIKALNO-NAGORE KONTINUALNO LIVENE ALUMINIJUMSKE ŽICE

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Ključne reči
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- kombinovani alat
- struktura
- mehaničke osobine

Abstract

The productivity of vertical upwards continuous casting of aluminium wires depends mainly on effectiveness of the cooling process in the mould.

The aim of this actual work is to investigate the structure of cast aluminium wires, depending on casting speed. The related mechanical properties such as tensile strength and hardness of investigated samples are determined.

Depending on the function of production, the optimal technological parameters (temperature of liquid aluminium, casting speed and cooling rate) for several wire diameters of continuous cast aluminium wires are recommended.

Izvod

Produktivnost vertikalnog kontinualnog livenja nagore aluminijumskih žica uglavnom zavisi od efektivnosti procesa hlađenja u alatu.

Namena ovde prikazanog rada je istraživanje strukture livene aluminijumske žice, koja zavisi od brzine livenja. Određene su odgovarajuće mehaničke osobine, kao zatezna čvrstoća i tvrdoća ispitivanih uzoraka.

Zavisno od namene proizvodnje, preporučeni su optimalni tehnološki parametri (temperatura tečnog aluminijuma, brzina livenja i brzina hlađenja) za nekoliko prečnika kontinualno livene aluminijumske žice.

INTRODUCTION

The method of vertical upwards continuous casting of metals and alloys (Fig. 1) presents continuous drawing of round profile metal (< Ø30 mm) through a graphite casting die mounted inside a water-cooled copper mould, immersed from the top to a definite depth in molten metal, /1/. The profile is drawn from the mould by means of a roller-driven drawing mechanism after which it is coiled.

Until recently that method was applied mainly in copper and copper alloy casting, /1-6/.

In the work process /7/ the basic possibility of efficient vertical upwards continuous casting of aluminium and its alloys was ascertained.

The results from the initial experiments confirmed the assumption that in comparison to the vertical upwards continuous casting of copper and copper alloys, the application of the method for casting of aluminium and its alloys is characterised by considerably lower productivity. While in the first case (copper casting), a speed exceeding 2000 mm/min is achieved (for profile Ø14 mm /2/), in casting of aluminium of the same size, the maximum speed is one order of magnitude lower (250 mm/min), /7/.

Obviously, the thermo-physical characteristics of the cast metal are of importance, namely, the specific thermal capacity and the latent crystallization heat at the temperature of transition from liquid to solid state.

The specific thermal capacity of aluminium at crystallization temperature is 900 J/kgK, /8/, i.e., considerably higher than that of copper (385 J/kgK). Considering also the higher latent heat of aluminium crystallization ($3.96 \cdot 10^5$ J/kg) compared to that of copper ($2.05 \cdot 10^5$ J/kg) one could expect significant differences in the technological parameters of the upwards continuous casting of copper and aluminium, as well as their alloys.

Beside the specific, adverse thermo physical parameters in the transition of aluminium from liquid into solid state during upwards casting, after a hard skin is formed in the crystallization zone, the metal shrinks and detaches from the cooled wall of the mould, /9, 10/.

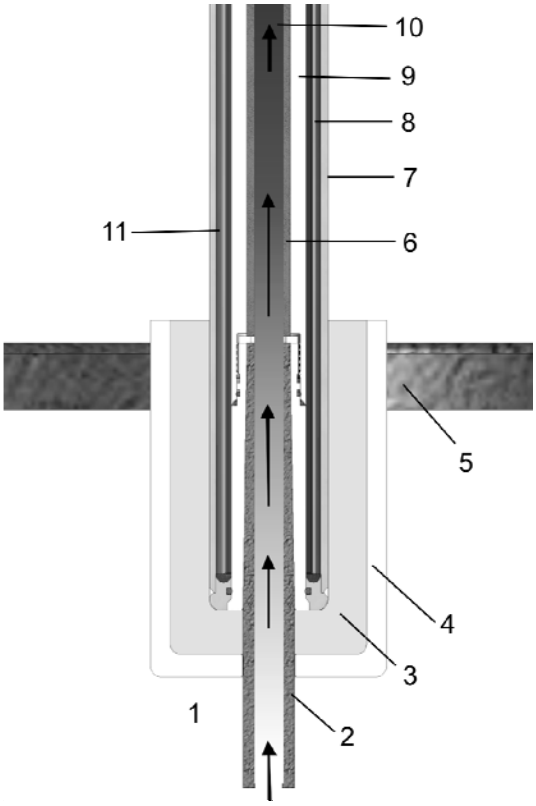


Figure 1. Scheme of upward continuous casting of metals, /7/. 1-liquid metal; 2-graphite casting die; 3-heat insulating wadding; 4-graphite-fireclay cup; 5-furnace crucible; 6-graphite bushes; 7-external mould pipe; 8-intermediate pipe; 9-internal copper mould pipe; 10-cast metal profile; 11-cooling water.

Slika 1. Shema kontinualnog livenja metala nagore, /7/ 1-tečni metal; 2-grafitni kalup; 3-ispuna toplotne izolacije; 4-grafitna-šamotna posuda; 5-jamasta peć; 6-grafitna podloga; 7-spoljašnji cevni kalup; 8-središnja cev; 9-unutrašnja bakarna kalupna cev; 10-profil izlivenog metala;11-rashladna voda.

During the classical continuous casting process (from the top downwards), the metallostatic pressure of the liquid metal in the tundish considerably delays the shrinking and detachment of the skin from the mould wall.

And vice-versa, in the case of vertical upwards continuous casting due to significant tensile stresses, the crystallized metal skin wears considerably thinner. The cross section of the air gap increases. The amount of heat abstracted from the section drastically decreases, the section core remains liquid, and the skin is thin. The mechanical strength of the metal is insufficient and the profile breaks.

In order to avoid the above-mentioned drawbacks of the classical method for upwards continuous casting, new ideas are adopted, to apply two-stage – indirect cooling, followed by direct cooling of the cast profile. It is implemented by means of an ingenious design of a new type of mould where cooling of the liquid metal in the graphitic casting die is indirect, and the cast profile is subjected also to direct cooling, /11/.

According to that new solution, the extra direct cooling is performed using an aerosol mix in the zone of metal crystallisation located immediately after the top of the graphitic casting die of the water-cooled mould (Figs. 2, 3). By means of flow rate control, the liquid from the aerosol mix evaporates from the surface of the metal section before reaching the graphitic casting die.

The different conditions of cooling of the cast profile result in expected changes in the metal structure and mechanical properties.

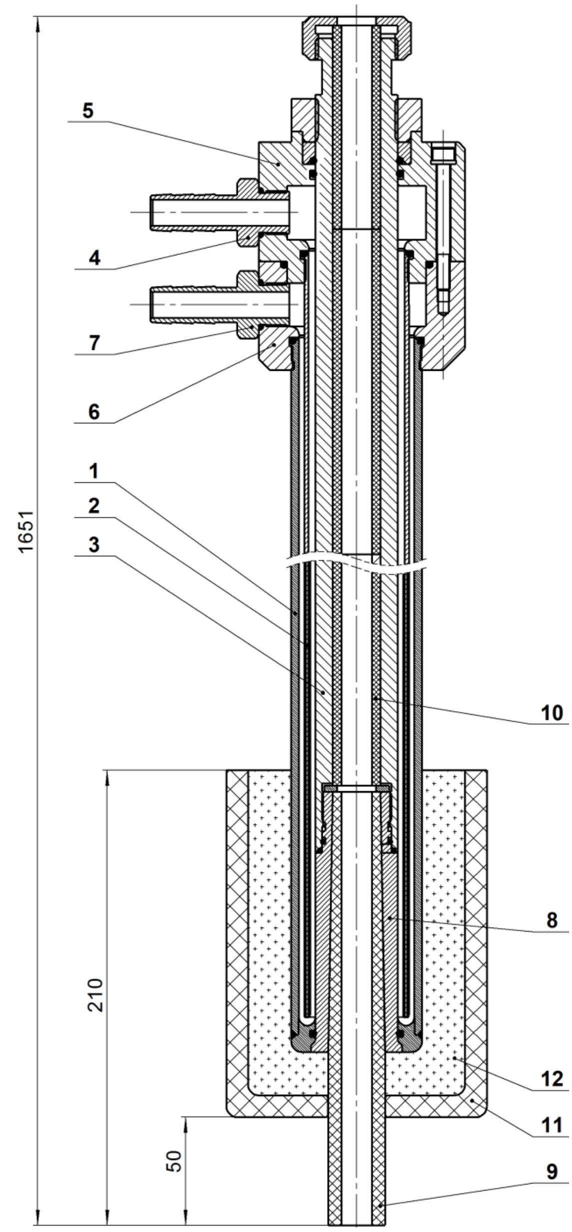


Figure 2. Classical water cooled mould for upward continuous casting of metals, /7/. 1-external mould pipe; 2-intermediate pipe; 3-internal copper mould pipe; 4-orifice "in-water"; 5-top flange; 6-bottom flange; 7-orifice "out-water"; 8-copper mould; 9-graphite casting die; 10-graphite bushes; 11-graphite-fireclay cup; 12-heat insulating wadding.

Slika 2. Klasični vodom hlađeni alat za livenje metala nagore, /7/ 1-spoljašnja cev kalupa; 2-središnja cev; 3-unutrašnja bakarna cev kalupa; 4-dovod vode; 5-gornja prirubnica; 6-donja prirubnica; 7-odvod vode; 8-bakarni kalup; 9–grafitni kalup za livenje; 10-grafitna podloga; 11-grafitna-šamotna posuda; 12-ispuna toplotne izolacije.

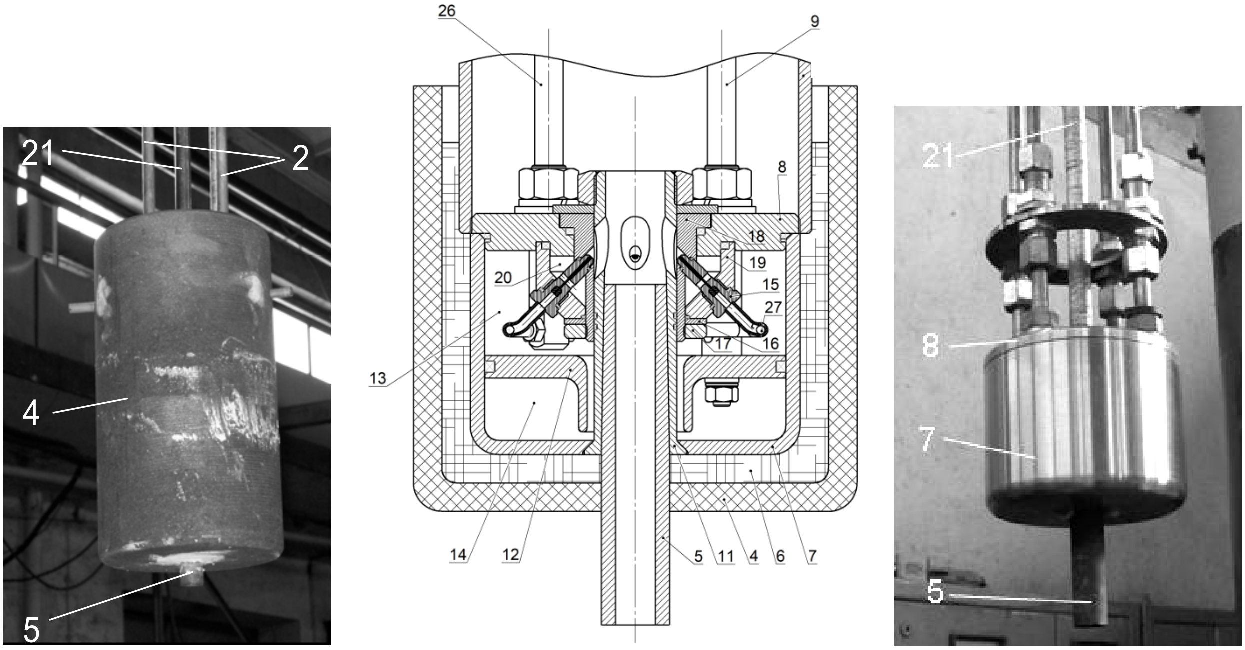


Figure 3. head of mould for upward continuous casting of metals and alloys with high thermal capacity.
2-supplier pipes; 4-graphite-fireclay cup; 5-graphite casting die; 6-heat insulating wadding; 7-cup-wise body; 8-cover;11-copper mould; 15-cooling nozzle; 21-cast aluminium wire Ø14 mm; 26-orifice “liquid cooling agent”; 27-annular collector.
Slika 3. Radna glava kalupa za kontinualno livenje metala nagore i legura velikog toplotnog kapaciteta
2-dovodne cevi; 4-grafitna-šamotna posuda; 5-grafitni kalup za livenje; 7-posuda; 8-poklopac; 11-bakarni kalup; 15-rashladna mlaznica; 21-livena aluminijumska žica Ø14 mm; 26-dovod „tečnog rashladnog agensa“; 27-prstenasti kolektor

STUDY OF VERTICAL UPWARD CONTINUOUS CAST ALUMINIUM PROFILE STRUCTURE, WITH DIRECT AND INDIRECT COOLING

The purpose of this work is to study the crystallization process with two-stage – direct and indirect cooling of aluminium during vertical upward continuous casting, and compare with casting in a classical mould (Fig. 1), /7/.

Aluminium purity is 98.6% with impurities of iron (1.32%), small quantities of magnesium and silicon (up to 0.3%). The casting temperature is 700°C.

Test samples, diameter Ø14 mm, of both moulds – classical and new with combined cooling are cast and studied.

The casting speed achieved with the classical mould was 180 mm/min, and with the new one 980 mm/min.

Macrostructural analysis (Fig. 4) showed that during operation of the classical mould the increase of casting speed from 180 to 250 mm/min results in the development of surface hot cracks (Fig. 5), due to comparatively slow cooling and formation of a thin skin of inadequate mechanical strength. The maximum speed at which good-quality wire is produced is 230 mm/min.

An optimal casting speed of 980 mm/min was achieved during new mould operation with applied indirect and direct cooling. The cast wire had a smooth surface without cracks. This is due to intensive direct cooling by a water-air emulsion and the obtaining of a sufficiently strong skin.

The casting temperature 700°C and iron content 1.32% are favourable for the formation of an eutectic structural component of the type Al-$FeAl_3$. At lower speed of the crystallization process (180 mm/min), this structural component can be detached from the alloy even at lower iron content, /9, 10/. In the solidification process and at low concentrations of Fe and Si, acicular $FeAl_3$ crystals form along grain boundaries of the α-solid solution of aluminium, with a skeleton-like shape of the eutectic Al-$FeAl_3$ in some areas. The fragile intermetallide $FeAl_3$ decreases the strength and plasticity of the alloy and may contribute to the formation of hot cracks in the casting process (Figs. 6 and 7).

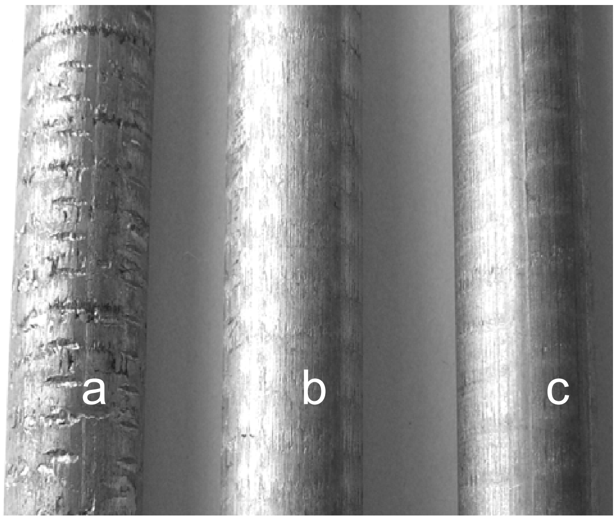


Figure 4. Upward continuously casted aluminium wire (Ø14 mm) with different moulds and speeds. Classical mould: *a*-high speed, 250 mm/min; *b*-low speed, 180 mm/min; new combined mould: *c*-high speed, 980 mm/min.
Slika 4. Aluminijumska žica (Ø14 mm) kontinualno livena nagore u različitim kalupima i brzinama. Klasičan kalup: *a*-velika brzina, 250 mm/min; *b*-mala brzina, 180 mm/min; novi kombinovani kalup: *c*-velika brzina, 980 mm/min.

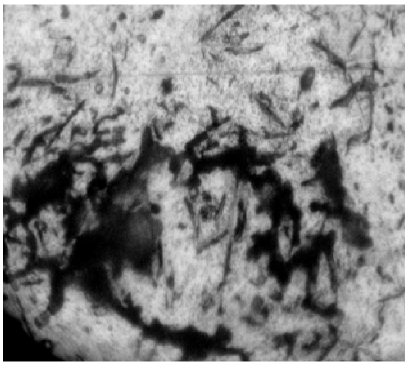


Figure 5. Hot fracture in wire skin, ×560. Classical mould, 250 mm/min.
Slika 5. Vrući lom u površinskom sloju žice, ×560. Klasični kalup, 250 mm/min

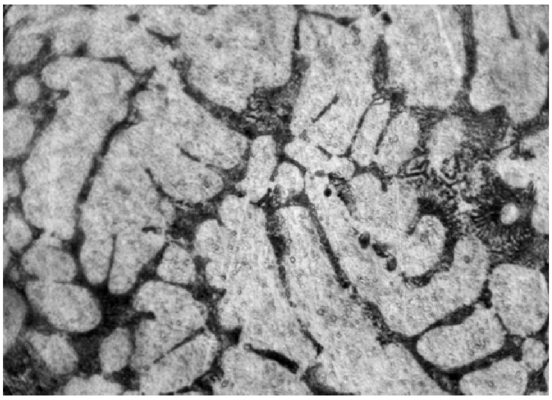
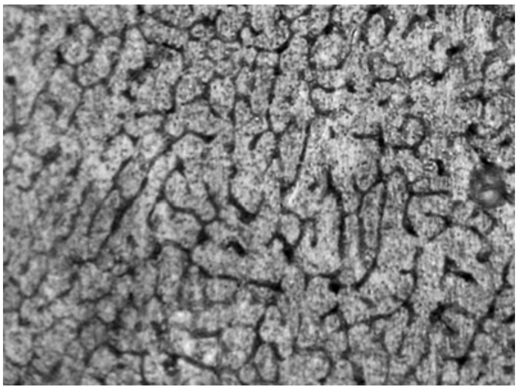
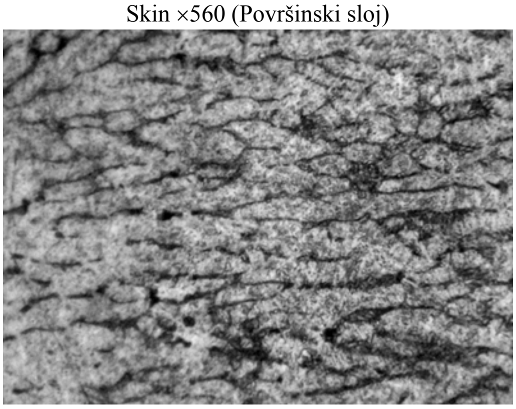


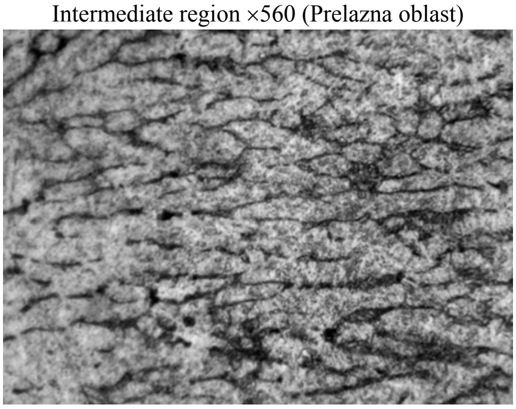
Figure 6. Precipitation of eutectic type at aluminium grain borders.
Slika 6. Talog eutektičkog tipa na granicama zrna aluminijuma



Skin ×560 (Površinski sloj)

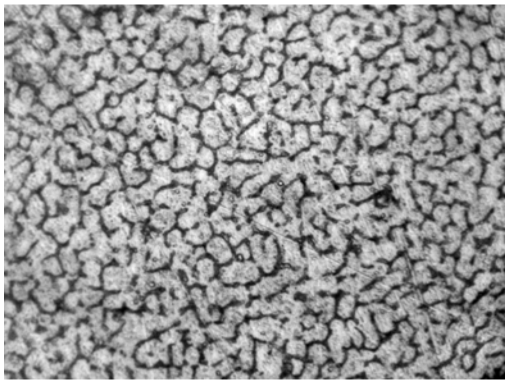


Intermediate region ×560 (Prelazna oblast)

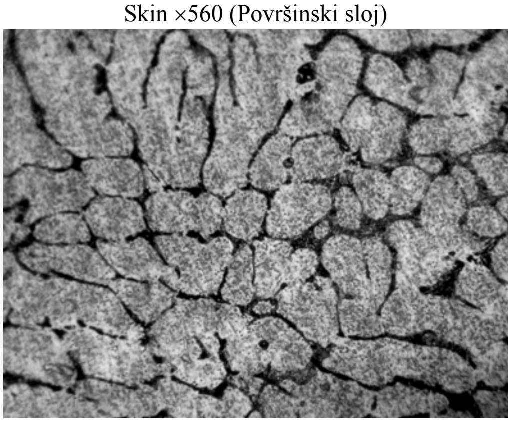


Central region ×560 (Centralna oblast)

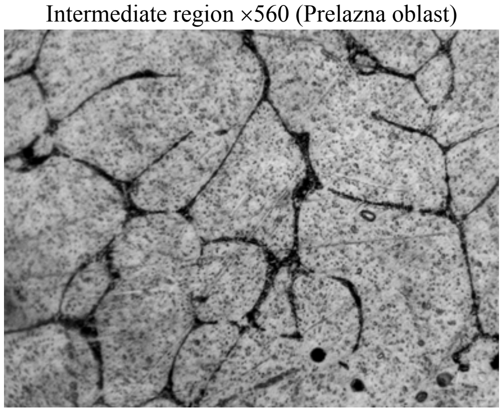
Figure 7. Classical mould for upward continuous aluminium casting, cast speed 180 mm/min.
Slika 7. Klasičan kalup za kontinualno livenje aluminijuma nagore, brzina livenja 180 mm/min



Skin ×560 (Površinski sloj)



Intermediate region ×560 (Prelazna oblast)



Central region ×560 (Centralna oblast)

Figure 8. New combined mould for upward continuous aluminium casting, cast speed 980 mm/min.
Slika 8. Novi kombinovani kalup za kontinualno livenje aluminijuma nagore, brzina livenja 980 mm/min

An eutectic component of Al-Si type is also precipitated along grain boundaries and has a negative effect on the mechanical properties of the metal without reducing its corrosion resistance.

In the case of aluminium casting under new technology conditions, the practically achieved casting speed is high enough to prevent precipitation of an intermetallide fragile phase along the boundaries of the matrix structure. Some small eutectic precipitations are uniformly distributed throughout the metal mass (Fig. 8).

In the case of casting with classical water-cooled mould, the heat of the cast metal is intensively removed along the whole height of the mould, with outlet temperature of the profile 25–30°C. This leads to oriented crystallization in the sub-skin zone (Fig. 7). The thickness of the fine-grain skin does not exceed 1 mm.

In the new mould, as a result of intense indirect and direct short-duration cooling of cast metal, a considerably thicker skin is obtained while the core remains liquid. Outside the intense cooling zone, the crystallization of liquid metal takes place in an air atmosphere at 50-80°C (atmosphere temperature above the liquid metal).

Thanks to the slow cooling, uniform-axis crystals are obtained, their size growing from the surface to the centre of the section (Fig. 8). The skin thickness has increased to about 1.8–2.2 mm.

The results from tensile strength tests of samples taken at different distances downstream of the crystallizers confirm the observed differences in section structures (Fig. 9). The Figure shows that the tensile strength remains practically constant, 23.6 MPa on the average, thanks to quick cooling of metal in the classical crystallizer.

In the new crystallizer, owing to comparatively slow crystallization, self-tempering of aluminium is observed, and at a distance of 4.5 m from the crystallizer, the initial tensile strength (average 17.4 MPa) decreases to 12.5 MPa on the average. The temperature at a distance of 4.5 m with different casting speeds is from 45 to 65°C.

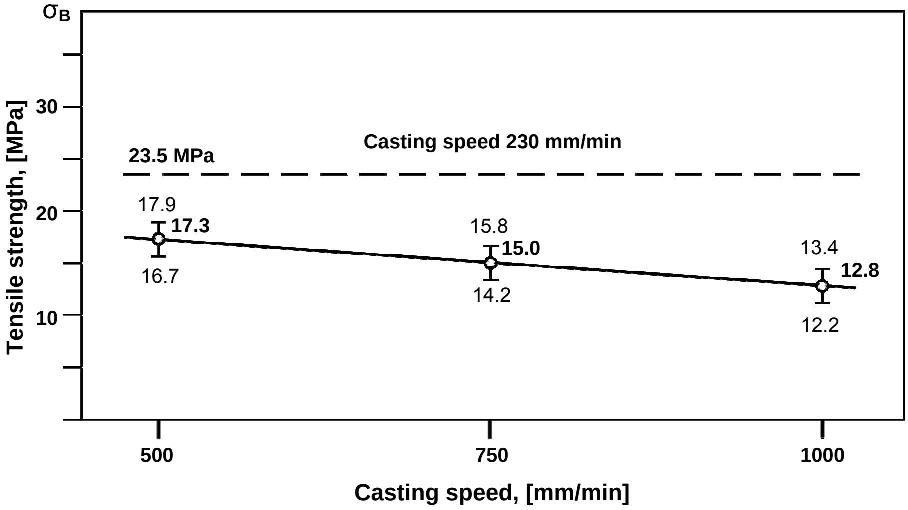


Figure 9. Tensile strength of continuous upwards casting of aluminium profile (∅14) as a function of casting speed. Classical mould: — — — — ; new combined mould: ————

Slika 9. Zatezne čvrstoća kontinualno nagore livenih aluminijumskih profila (∅14) u zavisnosti od brzine livenja. Klasičan kalup: — — — — ; novi kombinovani kalup: ————

CONCLUSIONS

The new mould with combined, indirect and direct cooling enables implementation of high speeds of upwards continuous casting of aluminium wire Ø14 mm, thanks to formation of a sufficiently thick and strong skin.

In the process of casting, the metal is self-tempered leading to certain decrease of its tensile strength on one hand, but improved plasticity on the other.

When determining the speed of vertical upwards continuous casting of aluminium, the optimum between desired mechanical properties of the metal and productivity shall be sought.

REFERENCES

1. US Patent 4802436-1989.
2. Katgerman, L., Continuous Casting of Aluminum, (Product Details), Maney Pub, 2004.
3. US Patent 6241004-2001.
4. US Patent 20030111207-2003.
5. US Patent 4858674-1989.
6. Sengupta, J., Thomas, B.G., Wells, M.A., *The Use of Water Cooling During the Continuous Casting of Steel and Aluminum Alloys*, Metallurgical and Materials Transactions A, Jan. 2005, Vol.36A, No.1, pp. 187-204.
7. Mihovsky, M., Hadzhiyski, V., *Vertical Upwards Continuous Casting of Aluminum Wires*, 10th National Conference of Metallurgy with International Participation, 28-31 May, 2007, Varna, Bulgaria.
8. Свойства элементов, справочник, под редакции проф. М.Е. Дрица, Металлургия, Москва, 1997
9. Фомин, Б.А., Москвитин, В.И., Махов, С.В., Металлургия вторичного алюминия: Учебное пособие для вузов, Москва, ЭКОМЕТ, 2004, ISBN 5-89594-093-5.
10. Колачев, Б.А., Елагин, В.И., Ливанов, В.А. Металловедение и термическая обработка цветных металлов и сплавов, М.: МИСИС, 2005, ISBN 5-87623-128-2.
11. Mihovsky, M., Hadzhiyski, V., Gavrilova, R., *New mould with combined – indirect and direct cooling, for vertical upwards continuous casting of aluminium wires*, Structural Integrity and Life, Vol.10, No2 (2010), pp.117-124.