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PROPERTIES ISOTROPY OF MAGNESIUM ALLOY STRIP WORKPIECES

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The paper discusses the issue of obtaining high quality cast workpieces of magnesium alloys produced by strip roll-casting. Producing strips of magnesium alloys by combining the processes of casting and rolling when liquid melt is fed continuously to fast rolls is quite promising and economic. In the process of sheet stamping considerable losses of metal occur on festoons formed due to anisotropy of properties of foil workpiece, as defined by the macro- and microstructure and modes of rolling and annealing. The principal causes of anisotropic mechanical properties of metal strips produced by the combined casting and rolling technique are the character of distribution of intermetallic compounds in the strip, orientation of phases of metal defects and the residual tensions. One of the tasks in increasing the output of fit products during stamping operations consists in minimizing the amount of defects. To lower the level of anisotropy in mechanical properties various ways of treating the melt during casting are suggested. Designing the technology of producing strips of magnesium alloys opens a possibility of using them in automobile industry to manufacture light-weight body elements instead of those made of steel.

***Key words*:** magnesium, melt, anisotropy, strip roll casting, homogenization, structure, strip workpiece, mechanical properties.

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One of the issues in casting flat workpieces to produce foil products consists in liquation of the principal doping components, which results in the anisotropy of their mechanical properties [4]. Annealed rolled material of magnesium alloys AZ31 and AZ61 are widely used to produce strips as stamping workpieces. In the process of sheet stamping considerable losses of metal occur on festoons (local swelling) due to anisotropy of the properties of foil workpiece, as defined by the macro- and microstructure and modes of rolling and annealing [9]. The principal causes of anisotropic mechanical properties of metal strips produced by the combined casting and rolling technique are the character of distribution of intermetallic compounds in the strip, orientation of phases of metal defects and the residual tensions. One of the tasks in increasing the output of fit products during stamping operations consists in minimizing the level of festoon forming. To provide the needed quality of end product one needs to achieve homogeneous properties of the strip produced by roll-casting machines both along and across the casted strip.

Magnesium alloys AZ31 and AZ61 feature strength characteristics similar to those of aluminium, and may effectively substitute it as strip materials used for lightweight structures [5]. In particular, the necessary prerequisite for wide application of magnesium in lightweight structures in automobile and machine building industries is the combination of plasticity and strength characteristics that provide for high level of deformation during rolling. Currently magnesium strips are only found on the market in insignificant volume and their price exceeds that of steel strips. It is explained by high costs associated with the technology of hot rolling of slabs formed of deformable magnesium alloys.

The basic cause of such unsatisfactory situation with the use of foil workpieces produced by continuous casting and rolling is poor quality of their resulting surface, presence of casting defects and high anisotropy of their mechanical properties [5, 7]. The grainy structure starts forming in the “quasi-equilibrium two-phase zone” and keeps growing while latent heat is freely emitted into the surrounding melt. Such equi-axial grains keep growing until they contact the crystallization front, and immediately after that the evacuated heat is transmitted via solid metal to water-cooled rolls. The rate of heat release increases noticeably then, and further growth of crystal lattice occurs in a single direction at a normal to crystallization front. That way a twin structure of the casting is formed, consisting of coarse grain dendrite areas connected with boundary zones of lattice cells.

Currently there is tendency to use highly doped aluminium alloys to produce foil products, increasing the contents of the principal doping components (Al, Si, Mn, Zn) in them, which results in inhomogeneous chemical composition of such workpieces all along them. X-Ray phase analysis of samples obtained has demonstrated the presence of various inter-metallic phases in the Mg – Al – Zn

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system, such as $((Al,Zn)_{49}Mg_{32}$, $Mg_{17}Al_{12}$ and the Al – Mn system, such as Al_8Mn_5, $Al_{11}Mn_4$, Al_8Mn_5, Al_9Mn_{11} phases [1, 11, 12]. To solve the problem one has to lower the liquation in the active zone as much as possible (that is the zone of final solidification of the strip in thin gauge of crystallizer rolls), expand the zone of equi-axial crystals and diminish the size of dendrite cell [2, 3]. Lowering the liquation of aluminium, manganese and silicium in the course of strip roll-casting is achieved by selecting rational temperature and speed modes of continuous casting, using electromagnetic mixing of metal in the gating distribution nozzle, and also by secondary cooling of the strip as it leaves the gauge between the crystallizer rolls. Stricter requirements on rolled strips of magnesium alloys, as well as the growing productivity of processing equipment call for further upgrades in casting technology using roller crystallizers.

The level of anisotropy in the mechanical properties of strip material may be defined via the coefficients of transversal deformation of samples cut out at angles of 0°, 45°, 90° to the direction of rolling μ_{21}, μ_1 and μ_{12} [1, 6]. The value of these coefficients and their stability make possible using profiled workpiece for deep drawing, its shape chosen with the account of anisotropy and of the need to cut the strip rationally. Microelectronic analysis of various strips of magnesium alloys has identified the influence of each element (Al, Zn, Mn) on metal structure (Fig. 1).

The distribution of elements before and after annealing of the strip workpiece of magnesium alloy was retrieved with the help of X-Ray structural analysis. It may be seen (Fig. 2) that manganese distributes freely across the full volume and depth of magnesium matrix, while zinc shows certain inhomogeneity after interim calcination.

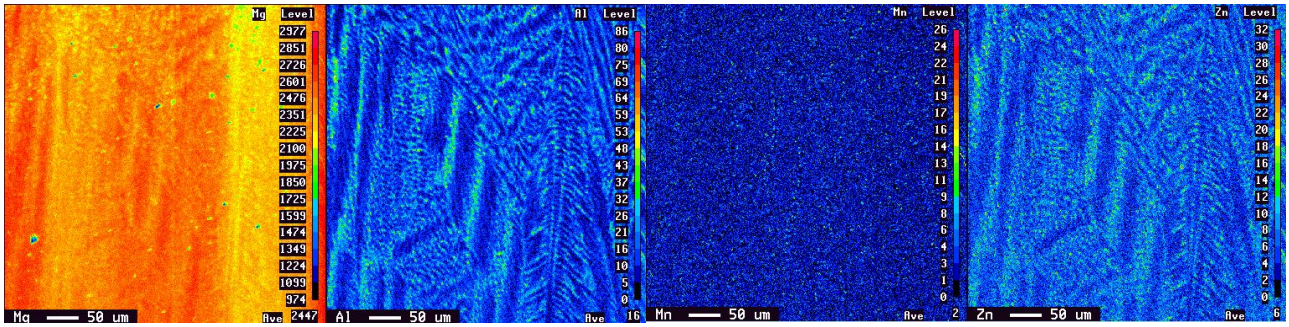

Fig. 1. Effect of distribution of Mg, Al, Zn, Mn in casted strip
(light areas indicate high concentrations of elements) [8]

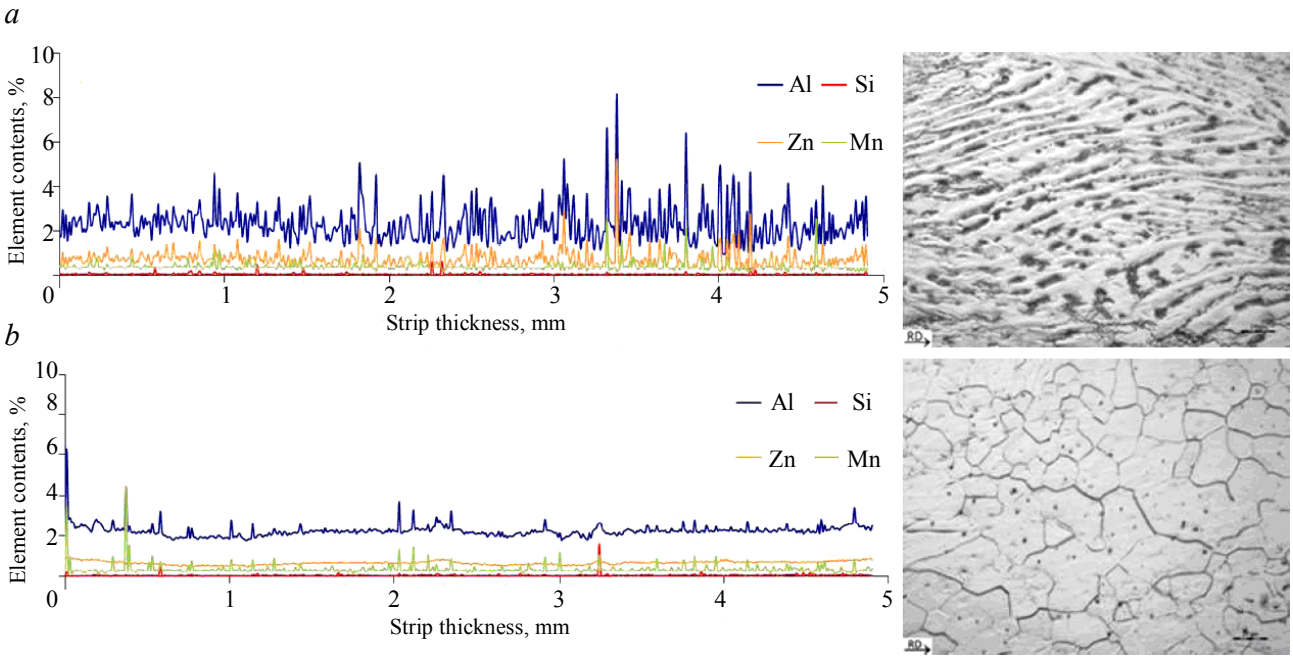

Fig. 2. Results of microelectronic analysis of distribution of elements across the strip depth before (*a*)
and after (*b*) thermal treatment [14]

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To study the effect of all these production factors combined on shaping the mechanical characteristics and anisotropy, as well as the stability of strip workpiece properties these were studied under various technological modes for both magnesium AZ31 and AZ61 (see the Table). For comparison purposes we considered the characteristics of strip workpieces retrieved before and after annealing. Rational mode of annealing results in a sharp improvement of mechanical characteristics and a drop in anisotropy.

Values of mechanical properties and anisotropy indicators for magnesium alloys before and after annealing

Alloy brand	$\sigma_{0,2}$, MPa	$\sigma_в$, MPa	δ, %	μ_{21}, α = 0°	μ_1, α = 45°	μ_{12}, α = 90°
AZ31 (before annealing)	62	92	14	0.455	0.326	0.485
AZ31 (after annealing)	82	112	19	0.411	0.306	0.413
AZ61 (before annealing)	74	108	15	0.394	0.393	0.387
AZ61 (after annealing)	94	128	18	0.364	0.323	0.337

Introduction of a comprehensive system of melt refining in the course of casting and rolling that covers all the stages of production helped to decrease festoon formation along the direction of lower resistance to deformation.

In the course of the study dependences were retrieved of festoon formation on chemical composition, presence of admixtures and technological parameters of the process. It was found that the position of festoons with respect to the direction of post-annealing rolling depends on the degree of preliminary compression. E.g., the size of the active zone being 30-40 mm, which entails 40% deformation of the strip in the course of combined process, resulted in the minimal formation of festoons during stamping. Employing the comprehensive treatment of melt at every stage of preparing it for casting (MHD-mixing, vibration treatment) has resulted in homogeneous distribution of intermetallic inclusions along all the planes of the workpiece, especially along its edges, due to lower zonal liquation. The distribution of anisotropy indicators μ_{ij} at different angles (in degrees) manifests a direct dependence on the number and distribution of inclusions in the workpiece [15, 16].

The analysis of zones of defect formation in the rejected products e showed that the principal factors defining festoon proneness during deep stamping are gas inclusions and accumulations of needle-shaped intermetallic phases of $Al_{11}Mn_4$ and Al_8Mn_5. Re-crystallized grains were found in the microstructure of samples from all the workpieces with varying contents of magnesium, taken after the final calcination. Parallel to the changes related to the contents of manganese, changes are observed in the shape and size of microstructural grains associated with changes in production technology. Microscopic analysis showed that the smallest grains in the structure are formed with higher contents of manganese. However, increasing the contents of silicium and manganese together results in elongation of these grains along the direction of rolling.

The analysis indicates that the maximum levels of anisotropy in strip properties are found along the edges of strip workpiece both before and after annealing. It becomes particularly manifested in case of increasing the contents of manganese followed by the respective depletion of the Mn/Si ratio to 2.0. Electromagnetic mixing is not capable of improving radically the macrostructure of foil workpiece due to low efficiency of the inductor, which may be related to high power losses in the solidified crust of the strip [17, 18]. Installing and positioning the inductor by the gauge of crystallizer rollers appears quite difficult in case the casting rate is changed, as well as organizing the cooling of workpiece surface at those roll-casting installations with melt fed from the side. Therefore there appears a need to employ different techniques for treating the crystallizing workpiece.

Within the concept of upgrading the equipment for strip roll-casting one needs to choose an optimal structure of the unit and a compression system, while selecting the depth of the crater and the length of deformation zone, plus changing crystallization conditions for the strip with the help of copper alloy bandages. The size of active zone depends on the power parameters of deformation and the diameter of crystallizer rollers. Physical phenomena taking place in the course of forming the strip

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in combination with deformation of its solid crust and solid-and-liquid phases are quite complex, so erroneously chosen parameters of the process result in insufficient process efficiency, formation of macrostructural defects and the appearance of internal cracks.

Calculations of crystallization of a magnesium strip during strip roll-casting following the model of quasi-equilibrium crystallization of the melt were performed with the account of boundary conditions for heat exchange formed in the gauge of crystallizer rollers by the updated cooling system (coolers). Temperature distribution was computed across the cross-section and width of the strip, as well as the ratio of liquid to solid phases and the stretch of the active zone. Following the analysis results and experimental data the share of solid phase in the solid-liquid zone was assumed not to exceed 25% and to end around 70% contents of the solid phase. The computed temperature distribution in magnesium strip may be used to define strip shrinkage or to calculate tensions and deformation during compression.

The algorithm of calculating compression in the gauge of crystallizer rollers makes it possible to account for the possible deformation of alloy with the change of its volume. Given the compression, the rate of casting and temperature field, the drive power may be computed needed to compress the strip and the deformation effort in the rolling cell. To forecast the possible development of cracks a mathematical model was developed of destruction of crystallizing aluminium alloys that involves the concept of continuous accumulation of diffused faults with the account of their possible healing. A particular feature of the combined casting and rolling technique is the presence of a multiphase transition layer that stays under tension due to deforming impact. The solid-and-liquid range of that layer, characterized by a newly formed crystallized carcass with liquid interlayers is capable of accepting the given load and getting deformed. However the deformation capacity is different for each brand of magnesium alloy and brittle inter-crystallite faults may occur in the process of crystallization.

When producing strips on strip roll-casting units it is most rational to refer to simplest theories of defect and fault accumulation in the process [6]. The process of destruction may be treated as a process of formation and propagation of micro-cracks that takes place against the background of the growing creep deformations characterized by the parameter w. One should note the generally differing mechanisms of the considered processes since brittle faults develop along the grains boundaries while viscous flow occurs inside the grains themselves. On the other hand if micro-cracks influence the creep, then the creep curves used to retrieve the coefficients for the equation of state reflect the cumulative effect since they are obtained for the samples cut out of the continuously roll casted strip.

Conclusions

Therefore, experimental tests and studies of magnesium strips with different contents of aluminium, manganese and silicium have demonstrated that to assess operational stability of strip roll-casting units and obtain the strip with minimum anisotropy of its mechanical properties one needs to consider several optional technical solutions:

- high degree of deformation of solid-and-liquid phase (50-60 %) and rolling the strip through an extra cell with individual compression control;
- compression of strip edges by independent rollers;
- strip compression in an extra cell oriented along the overall technological axis to exclude warping the strip profile.

Strip calibration shall be done in an extra pulling cell at a temperature of 200-260°C and complex high degree of deformation (100%), which brings the whole design of the installation to a full-scale strip roll-casting complex. Applying such upgraded sets will improve the structure of the axial zone of the strip considerably while also increasing the casting rate and decreasing the strip thickness. With combined roll-casting technique available new brands of Mg-based alloys may be mastered to produce rolled strips for various applications.

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Stability and low level of anisotropy of such roll-casting strips make them available for active stamping and deep pulling, their formation technology preventing the formation of festoons so that high output of quality end products becomes possible. Increasing the diameter of bolts of rolled products is a prerequisite for higher productivity of stamping units, which is another advantage of strip roll-casting.

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