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HOT FORGING OF HIGH STRENGTH AL-ALLOYS

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ABSTRACT

The paper presents the basic properties of materials and technology of hot forging of Al-alloy parts.
For alloys EN AW 2007 and EN AW 2024 the possibility of new technological procedure for casting Al-alloys under the influence of electromagnetic field was investigated. Such a procedure enables modification of microstructure and improvement of mechanical properties of ingots. In addition to that, the paper presents analysis of forging in manufacturing conditions for alloy obtained by extrusion with the application of suitable SC.SuperForge software for 3D problems. The obtained results show the equivalent stress distribution in work-piece which is being formed.
Key words: *hot forgings, Al-alloys, SC.SuperForge*

1. INTRODUCTION

Aluminium alloys of high strength have diverse and wide application in almost all fields of industry. Due to their specific properties, mainly the ratio of strength and mass, even though their production price is higher compared with iron alloys, aluminium alloys took up a significant position at the world market.
Aluminium alloys intended for hot forging enable obtainment of work-pieces of very accurate dimensions, with good-quality surface and with minimal need for additional forming. Realized deformation ratios in particular forging phases can be significantly higher than those realized at forging steel or copper alloys. Application of high strength Al-alloys (duraluminium) makes possible the manufacture of reliable parts with increased carrying capacity, e.g. in car and plane industry. The development of accurate forging, based on traditional hot forging, makes possible the manufacture of complicated forged pieces, with so called fibre structure which follows the contour of forged piece, of high-quality microstructure and of appropriate mechanical properties and measure tolerance. Figure 1 shows general influences on successful form filling and quality of realized forged piece structure.

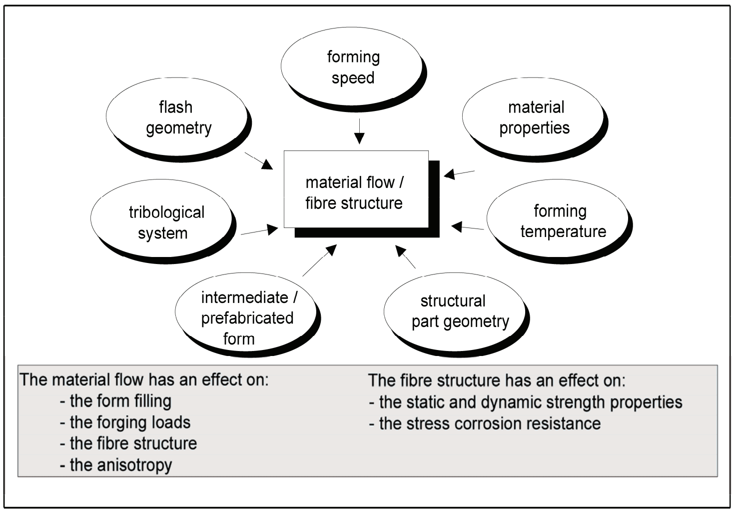


Figure 1 - Elements which influence the structure of forged piece [1]

2. ALLOYS FOR FORGING AND FORMING CONDITIONS

A large number of Al-alloys can be forged, ranging from pure Al to high strength alloys. Heat-treatable alloys of medium and high strength are most often forged, according to fig.2. These materials are very sensitive to change of forging temperature. At decreased temperatures, incomplete recrystallization leads to deformed and undesired microstructure. Large grains in non-homogenous structure lead to bad mechanical properties of forged piece. Increased deformation ratio in particular forging phases increases the strength of forged piece. Contrary to that, increase of forging temperature and prolongation of forming time leads to decrease of forged piece strength [2].

Temperatures of Al-alloys forging depend on type of alloys and lie in the interval between 320 and 480^{o}C, according to fig.3. Tools must be heated in advance, in order to avoid thermal deformation. Fig.3 also shows the main advantages and disadvantages of forging Al-alloy pieces. The main problem in forging Al-alloys is the need for precise maintenance of work-piece temperature, which is significantly influenced by deformation speed. Temperature intervals of forging are restricted and must be complied with.

When deformation speed increases, a part of conducted energy transforms into thermal energy, so attention must be paid to the type of machine on which the forming is performed (hammers, presses). It is well known that temperature and deformation speed have the opposite effect onto the strengthening process; increase of speed leads to increase of flow stress, higher temperature reduces strengthening.

Alloys applied in this paper are EN AW 2024 (AlCu4Mg1Mn) and EN AW 2007 (AlCu4PbMg). They are heat-treatable alloys and are intended for plastic processing. Their production and processing are long-term and expensive, because they involve a series of technological operations (modification, casting, homogenization, pressing, forming and thermal treatment).

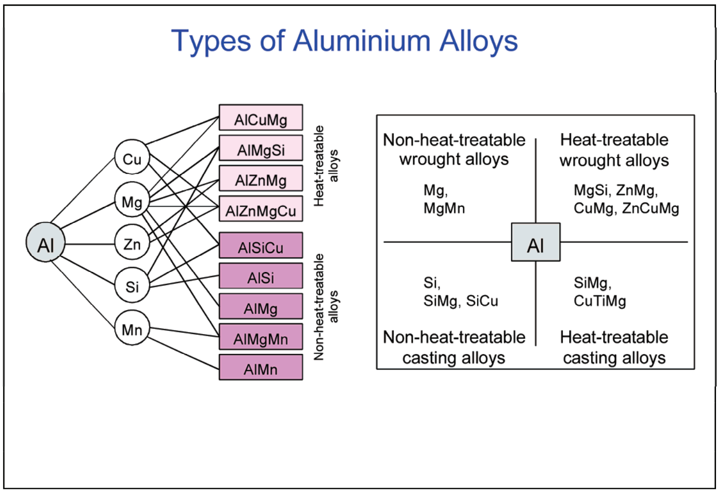


Figure 2 - Aluminium alloys for forging [1]

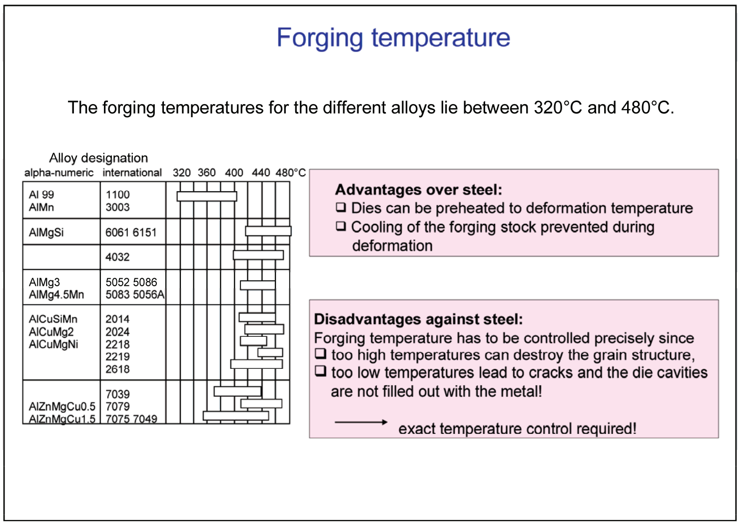


Figure 3 - Forging temperatures for some Al -alloys [1]

It is well know that conventional horizontal or vertical casting in dies, due to unbalanced strengthening conditions, leads to appearance of grain border segregations or dendrites. In addition to this, porosity, hot cracks and imbalance in grain size occur. All this leads to deterioration of mechanical properties of strength and tenacity first of all. With the aim of eliminating the specified disadvantages, various methods have been applied worldwide: powder metallurgy, ultra-sound and mechanical vibrations. Unfortunately, the procedures are either too complicated and expensive or insufficiently efficient. Literature sources have shown that the procedure of casting under the influence of electromagnetic field is much easier and more efficient [3,4].

During casting in the presence of electromagnetic field, the alternating current generates the time-variable magnetic field in melted mass, which in turn increases induced current in melted mass and ingot. Therefore, the melted mass is exposed to electromagnetic forces which were caused by interaction of induced current and magnetic field.
Generally speaking, the reason which leads to improvement of microstructure, reduction of porosity and stimulation of heterogeneous nucleation is the fact that forced convection generated by electromagnetic forces results in colder melted metal flow starting from edges towards the centre and vice versa. In that way, more balanced temperature field is established. Balanced temperature through cross section of ingot also reduces tensions which arise in course of strengthening. Reduction of metallurgical errors in ingots can also be expected.
This paper represents the researches which are the first attempt here to apply electromagnetic field in the procedure of Al alloys casting with the purpose of influencing the crystallization process in order to obtain modified microstructure and improved mechanical properties. In that way, the conditions were made which allowed avoidance of some technological operations in course of obtaining (modification) and processing (homogenization) of these alloys, which would lead to significant economic effect.

3. EXPERIMENTAL RESULTS

Chemical content of applied alloy EN AW 2007 (AlCu4PbMg) and EN AW 2024 (AlCu4Mg1Mn) is shown in table 1.

Table 1. Chemical content of alloys

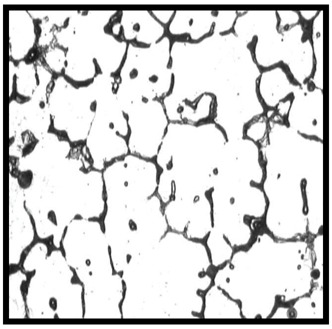
Content / Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ni	Ti	Pb
2007	0.30	0.30	3.92	0.80	0.95	-	0.02	0.004	0.02	1.1
2042	0.09	0.22	4.1	0.60	1.28	0.01	0.02	0.01	0.01	-

For melting alloys, induction furnace of medium frequency with capacity of 100 kg was used, with graphite crystallizer. Specimens (blocks) of alloy 2007, with diameter Ø50mm, were obtained by horizontal continual casting. Specimens of alloy 2024, with diameter Ø 60mm, were obtained by vertical continual casting. Drawing of blocks was performed impulsively (5mm backwards -14 mm forwards). The aforementioned crystallizer was located at the bottom of the furnace and the electromagnetic fields were positioned around the crystallizer with controlled work parameters (frequency, power of current fields, and number of windings in coil). Casting temperature was 720°C.
Specimen 1 was cast as measuring standard for comparisons, without the influence of electromagnetic field.
Table 2. shows some of the work parameters of casting. Frequencies were selected in broad diapason ranging from 1830 to 30Hz. Literature data [3] exist only for low frequencies (< 100 Hz). Since we had the opportunity to test the influence of high frequencies as well, such tests were also performed on the alloy of similar content (2007) with the alloy which is the main subject of our interest, i.e. 2024.

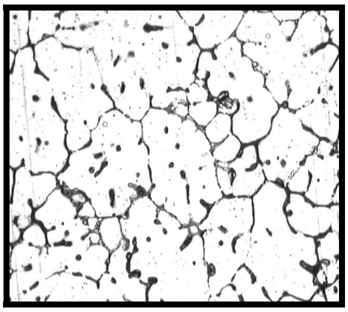
Table 2. Specimens labels and work parameters of casting

Specimen	Alloy	Frequency, Hz	Number of windings in the coil
Specimen 1	2007	0	40
Specimen 2	2024	50	40
Specimen 3	2024	30	40
Specimen 4	2007	1100	40
Specimen 5	2007	1830	40

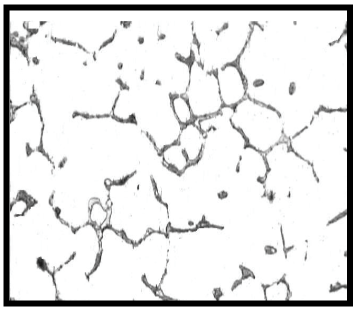
Qualitative and quantitative (width of secondary dendrite branches, DAS, width of inter-dendrite space, $L_{IMF,}$ and volumetric share of inter-metal phases, $V_{V\ IMF}$) microstructural analysis was performed on cross section of specimens (blocks). Optical microscope with automatic device for analysis of figure Leica Q500MC was used. The parameters which show best the dispersity of structure and are the consequence of strengthening conditions were selected for measuring. For selected specimens, mechanical properties were investigated as well ($R_{p0.2,}$ Rm, A_o and HB). Figure 4 shows characteristic microstructures of investigate specimens.



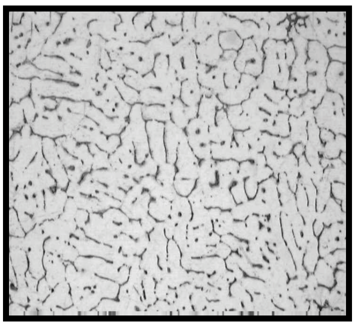
Specimen 1 (alloy 2007)



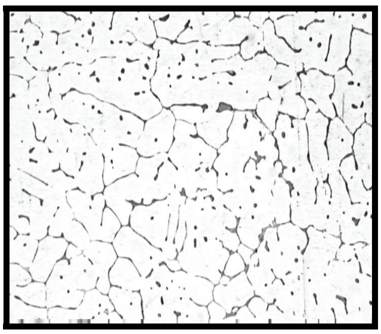
Specimen 2 (alloy 2024)



Specimen 3 (alloy 2024)



Specimen 4 (alloy 2007)



Specimen 5 (alloy 2007)

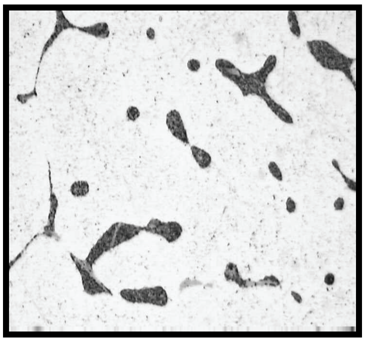
Figure 4 - Microstructure of investigated specimens

Microstructure is of dendrite-cell morphology of separation of hard solution Al, in all specimens. Along borders of dendrites and grains, inter-metal phases were extracted in the form of eutectic or separately. EDX analysis showed the presence of phases: Mg_2Si, Al_2Cu, Al_3Fe, Al_3Mg_2, Al_6Mn and Al_4Mn. In alloy 2007, lead particles were dispersedly arranged as well. It is obvious that the application of high frequencies led to obtainment of rougher structure in comparison to low frequencies.
Value distribution histograms for measured parameters show that the dispersity of structure increases with the decrease of field frequency. Also, it is obvious that the application of high frequencies has no effects on the improvement of microstructure, as expected. Quite contrary indeed, at 1830 Hz the structure was rougher compared to one obtained without the influence of electromagnetic field.
By detailed analysis of specimens, the presence of inter-dendrite porosity was established, the quantity of which decreases with the decrease of electromagnetic field frequency, which contributes to the better quality of ingots, and thus to mechanical properties. Since it was concluded that that there are no positive effects of high frequency onto the obtained microstructure, the investigations included only the mechanical properties of ingots obtained by application of frequency6 50Hz and 30Hz, but also of the one obtained without the influence of electromagnetic field. The values of mechanical properties are given in table 3.

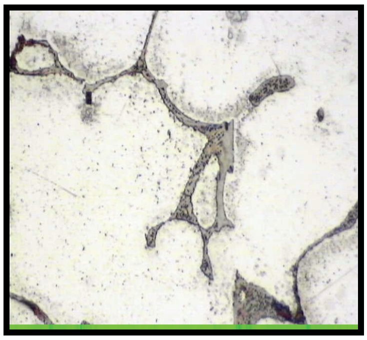
Table 3. Mechanical properties of ingots of alloy 2024

Specimen	$Rp_{0.2}$, MPa	Rm, MPa	A, %	$HB_{5/250/30}$
Spec.2. (50Hz)	198.04	243.20	1.20	93.5
Spec.3. (30Hz)	246.66	274.21	0.67	107.0

On the basis of previous microstructural analysis, such trend of change of alloy resistance properties, i.e. their increase, could have been expected. However, decrease of plasticity for specimen 3 can be interpreted by the appearance of rough continually extracted particles of IMF in relation to specimen 2. fig.5.



a)



b)

Fig.5. Particles of IMF in inter-dendrite space, specimen 2.(50Hz)-a; specimen 3.(30Hz)-b, Keller's reagent

However, one should bear in mind the fact that the values of mechanical properties for specimens of alloy 2024 cast without the influence of magnetic field were: $Rp_{0.2}$= 162.5MPa, Rm= 179.9MPa and A= 0.49%. This means that by the good combination of work parameters of casting increase of resistance properties can be achieved, and also the increase of plasticity by the use of microstructure control [4].

4. EXAMPLE OF AL-ALLOY FORGING

Further in this paper, concise analysis of forging of axis-symmetrical forged piece from the production programme of the company »Petar Drapsin – Forging Shop« from Mladenovac is presented. The initial piece has dimensions Ø50 x 125 mm. The material for forging is alloy AlCu4Mg1Mn, produced in two ways: by classic preparation for hot forming (modification, casting, homogenization, extrusion, thermal treatment) and by special casting procedure under the influence of electromagnetic field [4]. In this paper, the results for alloy obtained by the first fabrication procedure are specified. According to JUS C.C2.100, such alloys have high strength and are convenient for hot forming and strengthening by natural aging. Main properties of this alloy are given in table 4.

Table 1.Mechanical properties of EN AW 2024

Material	Tensile strength, Rm [MPa]	Flow limit, Rp [MPa]	Stretching at tearing, A10 [%]	Hardness acc. to Brinel
AlCu4Mg1Mn	440	310	8	115

Prior to forging, the tool is heated to the temperature of 250°C, and work piece to the forming temperature of 410-420°C. Forging is performed in a single operation, on electro-hydraulic press LASCO 1600. After forging, prescribed thermal forming is performed: 1- hardening (heating to 495±5°C at the duration of 90 minutes, cooling in water), 2- aging (heating to the temperature of 190°C, detention time is 11 hours). Flow curve for this alloy and working conditions (temperature and deformation speed) have the form:

$$K = 68.26 + 54\ \varphi^{0,1445}\ [\mathrm{MPa}]$$

Numerical simulation of the forging process was performed by famous specialized software MSC.SuperForm 2005. Work-piece geometry is axis-symmetrical, so the problem was solved as 2D, which significantly simplified the analysis procedure. The specified results are initial results in using this programme package, and they will serve as the introduction into the analysis of forming of parts of significantly more complex configurations. The simulation was performed in 395 steps, with automatic remeshing; model elastoplastic strengthening was used. Initial and limit conditions were adopted from recommendations and bases which exist within the programme itself and similar (eg. value of friction coefficient is 0,3) [5,6] .
Figure 6,7. shows the grid of elements in final forging phase, as well as a grid detail at the bottom of the work-piece. Basic geometry of work-piece and tool can also be seen in the figure (inner diameter of work-piece is 39 mm, outer diameter on the top is 70mm, and work-piece height is 94 mm). Forging is performed in classic way, in vertical plane, but, due to specific properties of modelling, graphs are given as if the forming was performed in horizontal plane (left part of the tool is motional).

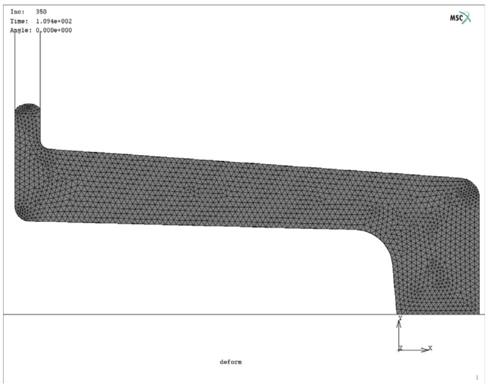


Fig.6. Work-piece geometry and grid outline

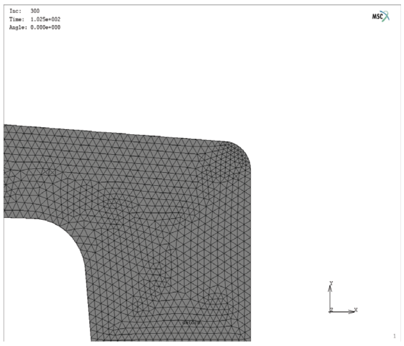


Figure 7 - Grid detail at the bottom of work piece at the end of forging

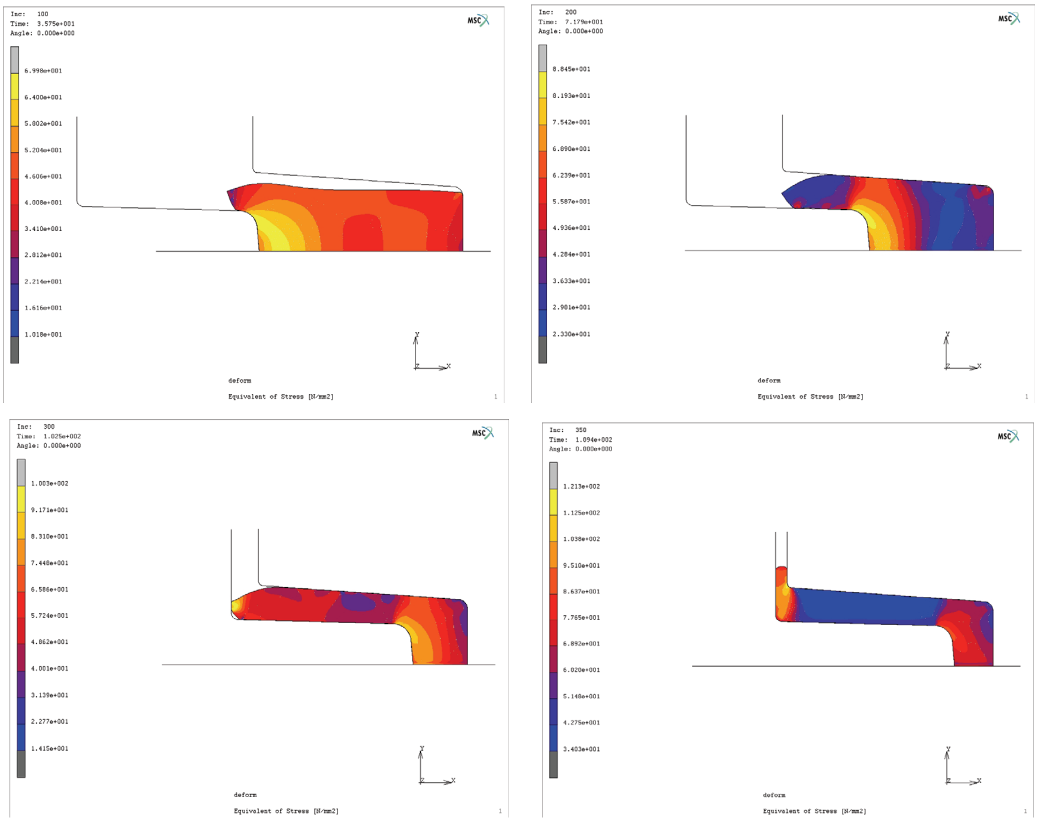


Figure 8 - Distribution of equivalent stress σ_e in different forming phases

Figure 8. presents the distributions of equivalent stress (σe) in several key phases of forming. Equivalent stress reaches its maximal values at the end of forming in phase of flash forging and it is 112,5 MPa in die radius zone. The values of stress in work-piece wall are highest at wall forming, and after that they decrease. More detailed analysis of material flow at forging over stress components, deformation fields etc, are not given in this paper, but even at such considerations the same conclusions are reached.

5. CONCLUSION

The results of investigation of electromagnetic field influence onto the quality of ingots of Al alloys 2007 and 2024 have shown that it definitely exists regarding the change of microstructure and mechanical properties. Thereat, only the application of low frequency fields has the positive effects (≤ 50Hz) which obviously changes strengthening conditions. Further work in this area should be focused towards finding optimal work parameters of casting with application of low frequencies, which will enable obtainment of ingots of such structural and mechanical properties which will make possible shortening of technological procedure of processing these alloys.

By hot forging of high strength Al-alloys, ingots with high-quality structure can be obtained, with required accuracy parameters, surface quality and mechanical properties. Unlike steel forging, for metal flow process and provision of high-quality microstructure of Al-alloy ingots, it is necessary to control the influence of temperature and deformation speed precisely.

Numerical analysis and application of finite elements method is an efficient tool for optimisation of forming process, tools construction and improvement of products quality. When developing parts of complex geometry with high requirements regarding quality, numerical tools and element of so called virtual production make possible reliable and economically justified designing of optimal technologies of Al-alloys hot forging.

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TOPLO KOVANJE AL-LEGURA VISOKE ČVRSTOĆE

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REZIME

U radu se navode osnovne karakteristike materijala i tehnologije toplog kovanje delova od Al-legura. Za legure EN AW 2007 I EN AW 2024 ispitivana je mogućnost novog tehnološkog postupka livenja Al-legura pod dejstvom elektromagnetnog polja. Ovakav postupak omogućava modifikovanje mikrostrukture i poboljšanje mehaničkih osobinama odlivaka. Takođe, u radu se navodi i analiza kovanja u proizvodnim uslovima za leguru dobijenu istiskivanjem, uz pomoć odgovarajućeg SC.SuperForge softvera za 3D probleme. Kao primer, navode se rezultati distribucije ekvivalentnog napona u komadu koji se oblikuje u različitim fazama obrade.