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IMPROVING THE CASTING PROPERTIES OF HIGH-STRENGTH ALUMINIUM ALLOYS

IZBOLJŠANJE LIVNOSTI VISOKOTRDNIH ALUMINIJEVIH ZLITIN

Dalibor Vojtěch, Jan Šerák, Ondřej Ekrt

Department of Metals and Corrosion Engineering, Institute of Chemical Technology, Technická 5, 166 28 Prague 6, Czech Republic, dalibor.vojtech@vscht.cz

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Al–Zn–Mg–Cu alloys are examples of high-strength alloys. After age-hardening they often possess tensile strengths of more than 500 MPa. However, their casting properties are relatively poor as a result of solidification intervals that are too wide. Therefore, they often require an extrusion, rolling, or forging treatment, and the production of small series of special parts can, as a consequence, be very expensive. In this study, an improvement in the castability and a reduction of the hot-tearing tendency was achieved by adding small amounts of appropriate elements (Ni, Mg and Si), which form a quasi-eutectic microstructure to reduce the solidification interval of the Al–Zn–Mg–Cu alloys. This improvement is demonstrated by a comparison of the casting properties of the quasi-eutectic Al–Zn–Mg–Cu–Ni–Si alloy with the $AlZn_7Mg_2Cu_1$ and $AlSi_{10}$ alloys. In addition, an appropriate heat-treatment procedure, which ensures the optimum mechanical properties, is described.

Key words: Al–Zn–Mg–Cu alloys, casting properties, solidification, eutectic

Zlitine AlZnMgCu so predstavniki zlitin z visoko trdnostjo. Po staranju dosežejo trdnost preko 500 MPa, vendar imajo majhno livnost zaradi širokega strjevalnega intervala. Zato se uporabljajo v ekstrudiranem, valjanem, kovanem itd. stanju, proizvodnja majhnih serij posebne oblike pa je zelo draga. V tem delu je bilo doseženo izboljšanje livnosti in zmanjšanje vročega trganja z majhnim dodatkom primernih elementov (Ni, Mg, Si). Zaradi tega nastane kvazievtektična mikrostruktura, ki zoži strjevalni interval zlitin AlZnMgCu. To izboljšanje smo dokazali s primerjavo kvazievtektične zlitine AlZnMgCuNiSi z zlitinama AlZn7Mg2Cu1 in AlSi10. Opisana je tudi primerna toplotna obdelava, ki zagotovi optimalne mehanske lastnosti.

Ključne besede: zlitine AlZnMgCu, livnost, strjevanje, evtektik

1 INTRODUCTION

Al–Zn–Mg–Cu alloys are typical examples of high-strength aluminium alloys. The microstructure of the as-cast alloy consists of α(Al) primary dendrites and a Zn, Mg-rich degenerate non-equilibrium eutectic at the dendrites' boundaries. The composition of the eutectic is controlled by the chemical composition of the alloy. Depending on the Zn and Mg contents, the $MgZn_2$ and/or $Mg_3Zn_3Al_2$ eutectic phases can be formed during solidification [1]. In the Al–$MgZn_2$ and Al–$Mg_3Zn_3Al_2$ quasi-binary phase-diagrams, corresponding eutectic temperatures of 470 °C and 489 °C are proposed [2].

For this reason, Al–Zn–Mg–Cu alloys are characterised by wide crystallization intervals (approximately 180 K), which leads to poor castability and an enhanced tendency to form hot tears. Because of these difficulties, the cast alloys are normally used after rolling, extrusion, forging, etc., and the production of small series of special parts can be very expensive.

The demand for relatively simple-shaped parts produced by casting technology has led to the research and development of high-strength Al–Zn–Mg–Cu-based alloys that possess improved casting properties. To obtain better properties, the temperature interval of the crystallization should be reduced as much as possible. The practical realization involves appropriate additions of elements, which leads to the formation of intermetallic eutectic phases (IPs). The formation of such eutectics (α(Al)+IP) results in a reduction of the liquidus temperature; and because the temperature of the non-equilibrium solidus is nearly constant, the width of the crystallization interval is decreased. As a result, an improvement in the casting properties can be expected. Research in this field has shown that additions of **Ni** and/or an appropriate combination of **Mg** and **Si,** can improve the casting properties [3-7]. These elements form the eutectic phases $\mathbf{NiAl_3}$ and $\mathbf{Mg_2Si}$ in the alloy.

For the mechanical properties of an alloy, it is very important that the appearance of new eutectic phases should not lead to a significant reduction in the plasticity of the alloy. In addition, the solid solution can be alloyed with sufficient amounts of Zn, Mg and Cu (e.g. $AlZn_6Mg_2Cu_1$) to provide for the possibility of precipitation hardening. The phase composition of quasi-eutectic alloys differs from that of classical Al–Zn–Mg–Cu alloys; therefore, a modified thermal treatment should be used. As proposed in [4], the thermal treatment for obtaining the optimum mechanical properties can consist of the following three stages: 1. Solution annealing at 460 °C, for the dissolution of the non-equilibrium degenerate eutectic. 2. Globularization annealing at 500–550 °C, for a spheroidisation of the eutectic particles. 3. Quenching in water followed by an artificial ageing, to obtain a desirable level of strength. For the 7xxx alloys, a tensile strength of more than 550 MPa is commonly obtained [8]. Sometimes, a two-step ageing is recommended, to suppress the susceptibility to intercrystalline corrosion and to accelerate the conventional single-stage process [9,10].

The aim of this investigation was to compare the casting properties of the **$AlZn_7Mg_7Cu_1Ni_3Si_3$** alloy with those of **$AlSi_{10}$** and **$AlZn_7Mg_2Cu_1$** alloys. It was shown in our study that the $AlZn_7Mg_7Cu_1Ni_3Si_3$ alloy comes closest to the quasi-ternary eutectic point and that it contains both the $NiAl_3$ and Mg_2Si eutectic phases. $AlSi_{10}$ (of technical purity), a widely used alloy with excellent casting properties, was chosen as a standard. The properties of the $AlZn_7Mg_2Cu_1$ alloy are comparable to those of the group of typical high-strength Al alloys with relatively poor casting properties. The second part of this work is a description of an appropriate heat treatment leading to desirable mechanical properties for the quasi-ternary eutectic alloy.

2 EXPERIMENT

Castability, one of the most important casting properties, can be determined by various methods, including the pouring of a melt into experimental moulds of branched shapes. The castability is usually assessed as the total length of the branches filled with metal after solidification. In our experiments, we used a casting with the so-called "sputnik"-type shape (**Figure 1**).

The tendency of the alloys to form hot tears in the semi-solid interval was evaluated by pouring the melts into a modified Tatura cast-iron mould. In this test the resulting castings have six branches of varying lengths, from 25 mm to 150 mm (**Figure 2**). The arrangement of branches is like a fan, and the cross-section of each branch is triangular. The widened parts at the end of each branch suppress the contraction during solidification, which is the cause of the hot-tears formation: the shorter the branches with hot tears, the higher the hot-tearing tendency (HTT) of an alloy.

Figure 1: The casting of "sputnik" type used for the determination of the castability of alloys

Slika 1: Ulitek vrste "sputnik", ki je bil uporabljen za določanje livnosti zlitin

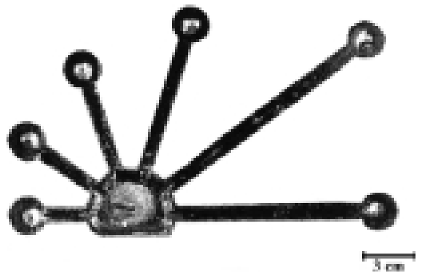

Figure 2: The casting used for the determination of the hot-tearing propensity of alloys

Slika 2: Ulitek, uporabljen za določitev tendence zlitin k vročim raztrganinam

The castability and HTT of an alloy depend on the pouring parameters. For this reason we evaluated both the effect of pouring temperature and the effect of holding time at the pouring temperature. The alloys were poured at (670, 700, 730, 760 and 790) °C after holding times of 0 (the alloy was melted and after sufficient homogenization (approximately 10 min) poured), 2 h and 4 h. The surfaces of the experimental metal moulds' cavities were covered with graphite and the moulds were preheated to 240 ± 10 °C. The melts were protected against oxidation by adding the fraction of Be 0.01 % in the form of an $AlBe_5$ masteralloy.

3 RESULTS

Figures 3, 4 and 5 show the castability (the total length of the branches of the experimental casting) of the three alloys that were examined. The castability is plotted as a function of both pouring temperature and

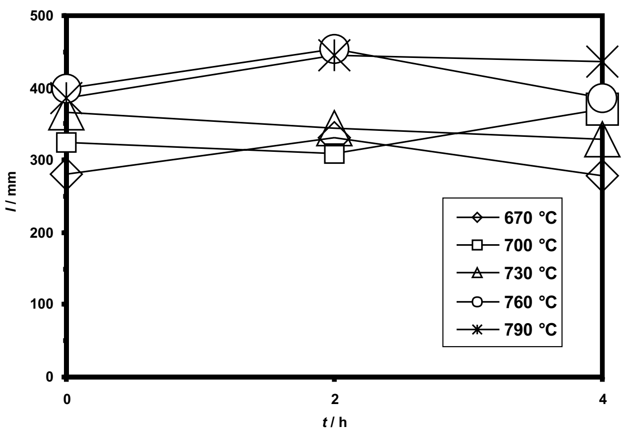

Figure 3: The castability (total length l of branches of experimental castings in mm) of quasi-ternary eutectic $AlZn_7Mg_7Cu_1Ni_3Si_3$ (Be) alloy as the function of pouring temperature and holding time at pouring temperature

Slika 3: Livnost (skupna dolžina l vej poskusnega ulitka v mm) ternarne kvazievtektične zlitine $AlZn_7Mg_7Cu_1Ni_3Si_3$ (Be) kot funkcije temperature litja in zadržanja pri tej temperaturi

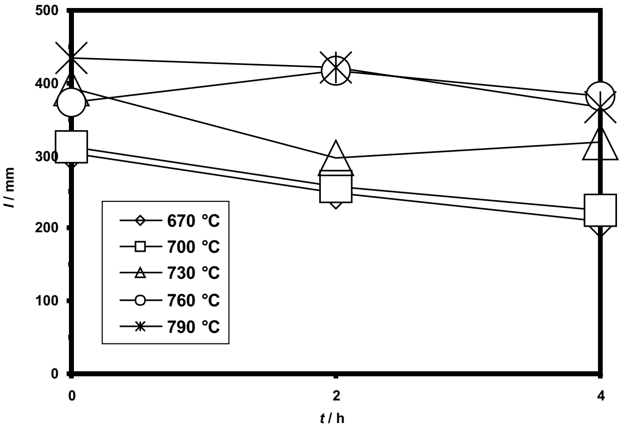

Figure 4: The castability (total length *l* of branches of experimental castings in mm) of $AlSi_{10}$ (Be) alloy as the function of pouring temperature and holding time at pouring temperature

Slika 4: Livnost (skupna dolžina *l* vej eksperimentalnega ulitka v mm) za zlitino $AlSi_{10}$ (Be) v odvisnosti od temperature litja in zadržanja pri tej temperaturi

holding time at the pouring temperature. We can see from these figures that the obtained values of castability lie within a broad range, and therefore require careful interpretation. It can be concluded, however, that the castability of the quasi-ternary eutectic alloy is similar to that of the Al–Si alloy. On the other hand, the castability of $AlZn_7Mg_2Cu_1$ alloy is poor at low pouring temperatures, whereas at higher temperatures it approaches that of the Al–Si and quasi-eutectic alloys.

The hot-tearing tendency (HTT) of the three examined alloys is summarised in Table 1. Since no significant influence of the pouring temperature and the holding time at the pouring temperature on the HTT was observed, Table 1 shows only the results of pouring at 760 °C. In the case of the $AlSi_{10}$ alloy, only a few of the longest (150 mm) branches have hot tears. This means that the HTT of this alloy is very low as a result of the narrow solidification interval. On the other hand, the HTT of the $AlZn_7Mg_2Cu_1$ alloy is large: the hot tears appeared even on the shortest (25 mm) branches. The wide solidification interval of this alloy is considered to be the main reason for the great propensity to form hot tears. Finally, the HTT of the quasi-ternary eutectic alloy is comparable to that of the $AlSi_{10}$ alloy, and it is significantly lower than that of the $AlZn_7Mg_2Cu_1$ alloy. In this alloy, hot tears were found mostly on the long (150 mm) branches, see **Table 1**.

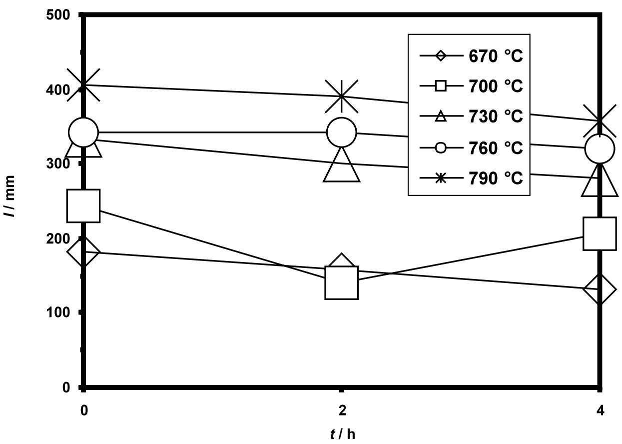

Figure 5: The castability (total length *l* of branches of experimental castings in mm) of $AlZn_7Mg_2Cu_1$ (Be) alloy as the function of pouring temperature and holding time at pouring temperature

Slika 5: Livnost (skupna dolžina vej *l* eksperimentalnega ulitka v mm) za zlitino $AlZn_7Mg_2Cu_1$ (Be) v odvisnosti od temperature litja in zadržanje pri tej temperaturi

In order to obtain the required mechanical properties of the quasi-eutectic alloy, an appropriate heat treatment should be applied. **Table 2** summarises the results of the globularization annealing. Despite a broad range of measured values, it is evident that the globularization step has a positive influence on the strength. The globularization at 520 °C leads to an increase in the strength by more than 50 MPa compared to the as-cast state.

Table 1: The hot-tearing tendency of the $AlSi_{10}$, $AlZn_7Mg_2Cu_1$ and $AlZn_7Mg_7Cu_1Ni_3Si_3$ alloy after pouring from 760°C as a function of the holding time at pouring temperature (HTT-length of the shortest branch with hot tears, N-no hot tears were found)

Tabela 1: Občutljivost za vroče raztrganine zlitin $AlSi_{10}$, $AlZn_7Mg_2Cu_1$ in $AlZn_7Mg_7Cu_1Ni_3Si_3$ po litju pri 760 °C v odvisnosti od časa zadržanja pri temperaturi litja (HTT-dolžina najkrajše veje z vročimi raztrganinami, N-ni bilo raztrganin)

$AlSi_{10}$			$AlZn_7Mg_2Cu_1$			$AlZn_7Mg_7Cu_1Ni_3Si_3$		
pouring temp. T_p/°C	time *t*/h	HTT/ mm	pouring temp. T_p/°C	time *t*/h	HTT/ mm	pouring temp. T_p/°C	time *t*/h	HTT/ mm
760	0	150	760	0	25	760	0	150
	2	150		2	25		2	150
	4	N		4	25		4	N

Table 2: Tensile strength of the quasi-eutectic alloy $AlZn_7Mg_7Cu_1Ni_3Si_3$ as a function of conditions of the globularization annealing

Tabela 2: Raztržna trdnost kvazievtektične zlitine $AlZn_7Mg_7Cu_1Ni_3Si_3$ v odvisnosti od temperature žarjenja za globulitizacijo

annealing temperature T_a /°C	annealing time t_a /h	tensile strength F_t /MPa
as-cast	0	191±6
500	2	221±14
500	4	230±13
500	6	212±40
500	8	212±14
520	8	246±15
520	16	246±9
540	16	225±26

Generally, the final step of the heat treatment is quenching in water followed by an artificial ageing. Age-hardening curves obtained after heating at 520 °C for 4 h, water quenching and ageing at different temperatures, are shown in **Figure 6**. A maximum hardness of over 200 HB can be achieved after ageing at 140 °C to 160 °C. After ageing at higher, as well as at

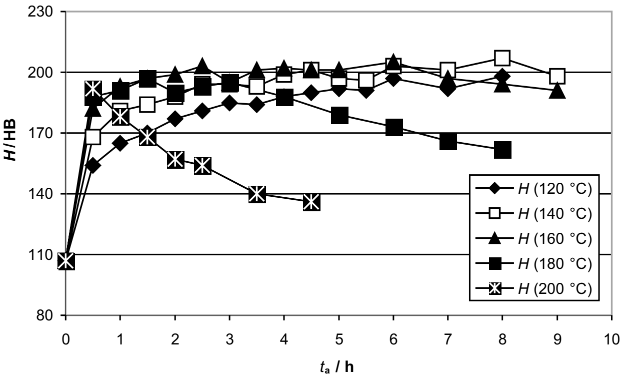

Figure 6: Age hardening curves of the the quasi-eutectic alloy $AlZn_7Mg_7Cu_1Ni_3Si_3$ obtained after heating at 520°C (4 hours), water quenching and ageing at different temperatures

Slika 6: Krivulja izločilne utrditve kvazievtektične zlitine $AlZn_7Mg_7Cu_1Ni_3Si_3$ po 4-urnem žarjenju pri 520 °C, kaljenju v vodi in staranju pri različnih temperaturah

lower, temperatures, the maximum hardness levels are slightly lower than 200 HB.

4 DISCUSSION

Generally, the casting properties of any alloy can be estimated from the width of its solidification interval. The nearly eutectic $AlSi_{10}$ alloy, with a very narrow solidification interval of approximately 10 °C, shows excellent castability and a low hot-tearing propensity. On the other hand, the $AlZn_7Mg_2Cu_1$ alloy is known to have a wide interval of approximately 150 °C. The ability of such a melt to fill a mould, especially one with a complicated shape, is limited. This is due to dendrites that form upon cooling and become obstacles to the continuous feeding of the melt. As a result, some parts of the mould remain unfilled. The wide solidification interval also facilitates the formation of the hot-tears, which is due to the presence of a thin layer of melt in the interdendritic regions in the alloy in its semi-solid state. Such a state has a very limited ductility and strength. During the solidification of the experimental castings (**Figure 2**), a volume change occurs and the alloy tends to contract. The contraction is, however, hindered by the widened parts at the end of each branch. Consequently, a tensile stress is induced and hot tears appear in the central part of the branches. The formation of the eutectic structure in the $AlZn_7Mg_7Cu_1Ni_3Si_3$, which narrows down the solidification interval to approximately 110 °C, has a considerable influence on both the castability and hot-tearing propensity. In particular, the reduction of the hot-tearing propensity is significant.

Table 2 shows that the globularization annealing leads to an increase in the strength of the quasi-eutectic alloy. It is known that upon heating, $NiAl_3$ and Mg_2Si eutectic particles, which are originally of irregular and elongated shapes, become progressively more spherical. This process happens more quickly for the Mg_2Si particles. In addition to the spheroidization, $NiAl_3$ particles also undergo a fragmentation. Both processes can be seen as sources of increasing strength, because the stress concentration in the globular and smaller particles is lower than in the case of elongated and coarse particles. After globularization annealing, water quenching and ageing should be performed in order to obtain the final hardness and strength. A hardness of above 200 HB can be achieved by ageing in the temperature range 140 °C to 160 °C. The ageing temperatures that are normally recommended for common Al–Zn–Mg–Cu alloys are within a similar range.

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