The effect of heat treatment conditions on the mechanical properties of sand cast alloy MRI 202S

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Abstract

Vehicle weight reduction is a key factor to meet stringent requirements for environment conservation, and this can best be achieved by the use of magnesium alloys that are the lightest structural materials. In light of this , creep resistant sand cast magnesium alloy MRI 202S is considered as promising candidate for engine block and other heavy powertrain components to be used in premium high performance cars.

Heat treatment is a very important factor for achieving a required combination of service properties of MRI 20S. It should be selected based on compromise between mechanical properties requirements and commercially acceptable holding time at solid solution treatment and particularly at aging.

The present paper addresses and discloses the effect of different heat treatment regimes on tensile, fatigue and creep properties of MRI 202S alloy. It was shown that there is relatively wide temperature-time window for solid solution treatment and aging of the MRI 202S alloy, which allows achieving optimal combination of service properties.

Introduction

Increasing environmental concern is one of key factors promoting attractiveness of magnesium alloys as valuable structural materials in applications requiring weight reduction and fuel economy. This is particularly relates to automotive and aerospace industries where reduction of fuel consumption and correspondingly fuel emissions are mandatory [1-3].

Major contributors to the weight of any vehicle are powertrain components, particularly engine block. In light of this, recently developed, high-performance gravity casting alloy MRI 202S [4,5] is a promising candidate for using in such large and heavy components for which sand casting is preferable production process. This alloy has good castability, is pressure tight and fully weldable. Excellent short-term elevated temperature strength and superior creep resistance enable to use this alloy at temperatures up to 200-250°C [4,5].

MRI 202S alloy is based on the Mg-Nd-Zn-Zr alloying system with small additions of oxidation inhibiting elements like Y and /or Ca. The principal alloying element is Nd that has maximum solubility in solid magnesium around 3.5 wt% which decreases sharply at room temperature. This factor is very important to enable remarkable precipitation hardening on the aging stage. Zirconium confers extreme grain refinement and casting integrity while Zn in the concentration range of 0.2-0.5% improves castability, strength and creep resistance.

The alloy develops the best combination of properties in the fully heat-treated T6 condition, which includes solid solution treatment, in order maximally dissolve alloying elements such as Nd, Y and Zn followed by forced-air or hot water quench and artificial aging in which precipitation hardening takes place [4,5]. According to [4], the standard full T6 treatment for MRI 202S includes solid solution treatment at 540°C for 5-7 h, hot water quench with subsequent aging at 250°C for 2-5 h. The high temperature solution treatment is designed to provide maximum practical solubility of the alloying elements while accelerated cooling maintains these elements in solid solution and the aging allows the required degree of precipitation hardening to occur.

However, for some applications such as engine block when Al alloy liner is cast-in into magnesium block, the solid solution treatment at 540°C may lead to the separation between magnesium alloy and aluminum liner. Therefore the alternative heat treatment based on lower solid solution temperature is required. On the other hand, this heat treatment should also provide sufficient supersaturation of the solid solution and thereby create adequate driving force for the precipitation hardening process over following aging.

In addition, reducing of solid solution treatment of MRI 202S alloy will reduce the temperature differential between the solution treated component and the cooling media. This should result in a reduction in the level of residual stresses induced during cooling/quenching.

Experimental

The sand cast bars with a 18 mm diameter and a 150 mm length were used for evaluating the effect of different heat treatment conditions on the mechanical properties of MRI 202S alloy.

Heat treatment was curried out in electrically heated furnace with forced CO_2 circulation as the protective atmosphere. This furnace provides uniformity of temperature throughout its volume within ±3°C. of the control set point.

Metallographic examination was performed using scanning electron microscope equipped with EDS spectrometer.

Hardness was measured using HRF scale of the Rockwell hardness test.

Tensile tests at room temperature were carried out on fully machined samples in accordance with ASTM B557M standard.

Fatigue tests were performed on specimens with a continuous radius between ends in accordance with ASTM E466 standard. The specimens had the radius of curvature 260 mm, the diameter of test section 6 mm and the grip diameter of 11 mm. The fatigue specimens were subjected to constant stress-induced fatigue test, which was conducted on rotating beam machine at R= -1.

The S-N curve (Woeler curve) was build using data, in which each point implies a number of cycles of a fractured specimen at a given stress level. The situation when a specimen survived over 10^8 cycles considered as a runout.

The confidence level was determined using Owen statistical approach [6]. Mean S-N curve of finite life fatigue region was constructed using Basquin equation:

$$S_a = S_f^{`}(2N_f)^b,$$

where S_a – is the fatigue strength, b is the fatigue strength exponent, S_f` is the fatigue strength coefficient and $2N_f$ is the number of reversals to failure.

Creep tests were carried out at the temperature range of 175-250°C in accordance with ASTM E139 standard.

Results and discussion

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The typical microstructure of MRI 202S in as cast condition is shown in Fig.1. In as cast condition MRI 202S has fine-grained microstructure with discontinuous network of $Mg_{12}Nd$ compounds in the form of a degenerate eutectic at the grain boundaries and between the magnesium dendrite arms. In some cases Nd atoms were partially substituted by Y atoms in very small proportion. In addition, the zirconium- rich coring is seen in most of magnesium alloy grains. These cores are believed to be the products of the peritectic reaction taking place over solidification [7].

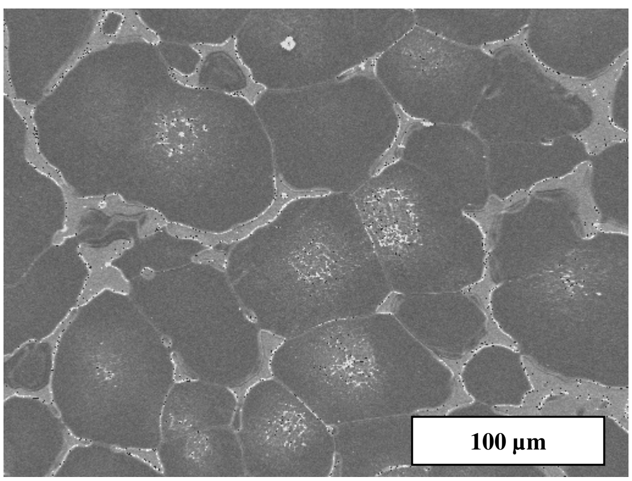

Fig. 1. The microstructure of as cast MRI 202S showing coarse $Mg_{12}(Nd,Y)$ intermetallics at grain boundaries and the zirconium-rich coring within the grains (secondary electron image)

The heat treatment conditions to be selected should improve this coarse microstructure and provide a balance between mechanical property requirements and commercially acceptable holding times at solid solution treatment and subsequent aging.

As it was already indicated, conducting solid solution treatment of MRI 202S alloy at lower temperature would reduce the temperature differential between the solution treated component and the cooling media. This should result in a reduction in the level of residual stresses induced during cooling/quenching.

The effect of solid solution treatment temperatures of 520°C, 495°C and 450°C was evaluated by testing of tensile specimens at room temperature. In all the above cases, the standard quenching media - hot water at 80°C and standard aging conditions - 250°C for 3.5 h were used. Furthermore, the common solid solution treatment temperature of 540°C was used to provide baseline properties. The results of tensile testing are presented in Table 1.

Table I. The effect of solid solution treatment temperatures on the room temperature tensile properties of MRI 202S-T6 alloy

Solid solution temperature [°C]	TYS [MPa]	UTS [MPa]	E[%]	UTS [MPa]
540	163±4	250±8	7±1	250±8
520	160±7	245±9	6±1	245±9
495	155±4	240±4	6±1	240±4
450	105±6	193±7	5±1	193±7

Reducing the solution treatment temperature of MRI 202S alloy leads to a reduced concentration of vacancies and atoms of Nd and Y within solid solution and consequently to lower driving force for the precipitation hardening process over subsequent aging. This in turn results in an overall deterioration of the mechanical properties of the alloy. The above findings are confirmed by the metallographic examination (Fig.2)

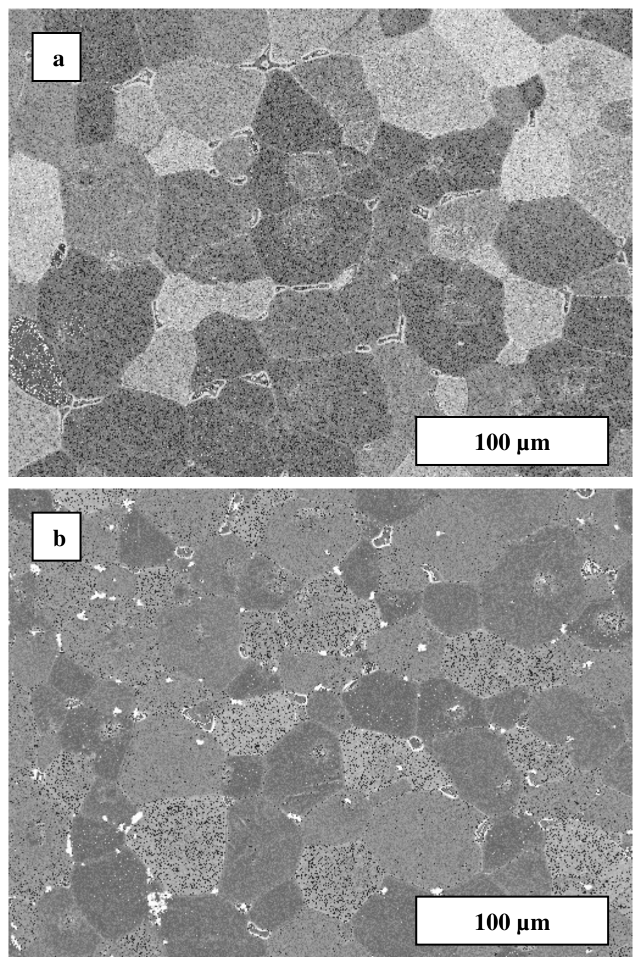

Fig. 2. The microstructure of MRI 202S –T6 after different solid solution treatments (secondary electron image)
a- 540°C; b- 495°C

As can be seen from Fig.2, more insoluble eutectic precipitates are present in the microstructure after solution treatment at 495°C.

Another important factor that could affect both mechanical properties and residual stress levels is quenching media. Therefore hot water at 100°C, compressed air and still air were evaluated as alternative quench media for MRI 202S-T6. In these experiments regular solid solution treatment at 540°C for 6 h followed by aging at 250°C for 3.5 h was used. The results obtained were compared to those of MRI 202S-T6 in the standard condition, i.e. quenched in water at 80 °C (Table 2).

Table II. The effect of quenching media on the room temperature tensile properties of MRI 202S-T6 alloy

Quenching media	TYS [MPa]	UTS [MPa]	E[%]
Water at 80°C	163±4	250±8	7±1
Water at 100°C	166±5	248±10	6±1
Forced air	162±4	245±8	6±1
Still air	159±6	243±9	8±1

As can bee seen from table 2 there is very limited effect of variation in quenching media on the tensile properties. However it is evident that still ambient air cool would appear the most favorable quenching media in terms of inducing residual stresses. This fact is of prime importance at heat treatment of complex castings. In addition, using of still ambient air is the cheapest solution because does not require additional material and equipment cost.

As it is well known and documented the aging schedule including temperature and duration is one of the most important factors affecting the effectiveness of the precipitation hardening process in Mg-Zr-RE alloying systems [7,8]. In present work the effect of aging parameters was studied on samples that were solid solution treated at 540°C for 6 h and hot water (80°C) quenched. These samples were subjected to aging at 200, 225 and 250°C for up to 100 h. Then the HRF hardness measurements were carried out (Fig. 3). As it was expected, higher aging temperature results in accelerated age-hardening kinetics and shifting aging peak towards shorter time: from 8h at 200°C to 0.1h at 250°C. However, the peak hardness values were similar for all the three aging temperatures. In light of these results, one can conclude that the aging temperature of 250°C is preferable compared to two other temperatures.

Despite of evident advantages associated with high-temperature solid solution treatment (540°C in the case of MRI 202S alloy) in some cases when magnesium alloy is in conjunction with aluminum one as it takes place in an engine block, the compromise solid solution treatment is required. Therefore it was of prime interest to compare the mechanical properties of the MRI 202S alloy after conventional T6 heat treatment and alternative heat treatment based on low temperature solid solution treatment at 495°C but with longer soak time for 9 h. The quenching media was still ambient air. In order to compensate longer solid solution soaking the aging time at 250°C was shorten to 1 h.

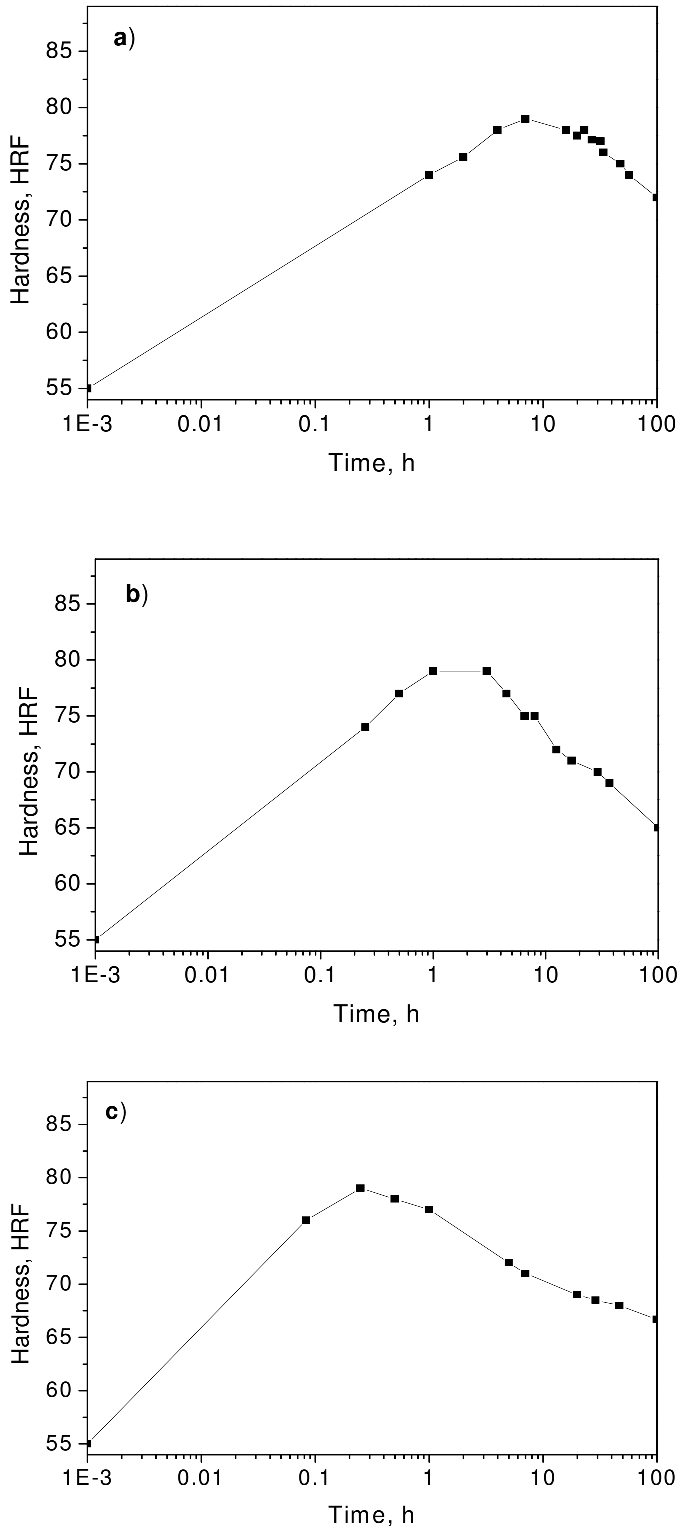

Fig.3.Variation of the MRI 202S –T6 alloy hardness depending on aging time at 200^0C (a); 225^0C (b) and 250^0C (c)

The results of comprehensive tests that included tensile tests at room temperature and 175°C, ambient fatigue tests and creep tests at 175-250°C under stresses of 75-150 MPa are shown in tables 3-4 and Fig.4.

Table III. The effect of T6 heat treatment conditions on the mechanical properties of MRI 202S alloy

Properties	540°C for 6 h + 250°C for 3.5h	495°C for 9 h + 250°C for 1h
TYS (MPa) at 20ºC at 175ºC	155±5 143±7	140±5 132±6
UTS (MPa) at 20ºC at 175ºC	273±4 236±9	235±7 201±9
E (%) at 20ºC at 175ºC	7±1 12±3	7±1 13±3
Stress [MPa] to produce 0.2% creep strain for 100 h at 200ºC	120	105

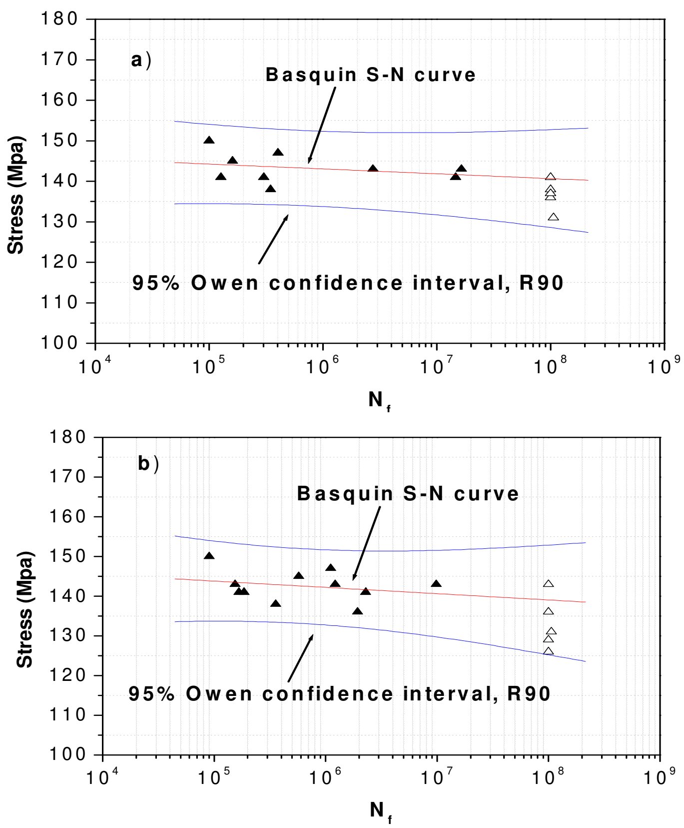

Fig. 4. Fatigue behavior of the MRI 202S –T6 alloy depending on heat treatment conditions
a-540°C for 6 h+250°C for 3.5h; b-540°C for 6 h+250°C for 1 h

Table IV. The Basquin equitation parameters of MRI 202S-T6 alloy depending upon heat treatment conditions

Heat Treatment	$S^{`}_{f}$ [MPa]	*b*	*Fatigue limit [MPa]*
495°C for 9 h +250°C for 1h	152	-0.005	138
540° C for 6h +250°C for 3.5 h	150	-0.004	139

All the results obtained clearly indicate that there is now significant difference in tensile, creep and fatigue properties of MRI 202S alloy specimens that were heat treated according to the two regimes.

Conclusions

Sand cast alloy MRI 202S has relatively wide operating window for performing full T6 heat treatment in order to achieve optimal combination of service properties.
Still ambient air cooling is preferable quenching media for complex MRI 202S castings.

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