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Mechanical and Metallographic Analysis of Hot Rolled Spray Formed Aluminium-Magnesium- Scandium Alloys

Th. Herding[1], O. Kessler[1], G. Tempus[2], F. Hoffmann[1], P. Mayr[1]

[1] Stiftung Institut für Werkstofftechnik, Badgasteinerstraße 3, 28359 Bremen, Germany
[2] Airbus Deutschland GmbH, Hünefeldstraße 1-5, 28199 Bremen, Germany

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Abstract

The addition of scandium to aluminium alloys offers the possibility to raise the strength by precipitation hardening. Al-Mg-Sc alloys are also excellently weldable and have a high corrosion resistance. But with conventional alloying methods only a low amount of scandium can be dissolved in aluminium alloys. By using higher cooling rates during solidification more scandium can be retained in supersaturated solid solution. This was realised by spray forming flat products. The flat products have been hot rolled at different temperatures. After hot rolling the microstructure and properties of the sheets were compared with the as sprayed flat products.

1. Introduction

The addition of scandium to aluminium-magnesium alloys leads to a number of interesting improvements. These are higher hardness and strength as well as, increased recrystallisation temperature. All improvements arise from Al_3Sc precipitations forming during aging of the alloy. These precipitations are coherent and have an ordered face centred cubic $L1_2$ structure. They raise the hardness and strength by hindering the movement of dislocations and increase the recrystallisation temperature by inhibiting grain boundary movement. Scandium is the transition element with the highest effect in increasing the recrystallisation temperature in aluminium alloys (Davydov et al. [1]). The weldability of aluminium-magnesium-scandium alloys is also well known (Lenczowski et al. [2]). The solubility of scandium in aluminium is fairly low by using conventional metallurgical methods (0.4 wt.% at a temperature of 655°C [1]). Toropova et al. [3] showed that it is possible to raise the solubility of scandium by increasing the cooling rate during solidification of the alloy. Such kinds of alloys can not be solution heat treated, because the scandium concentration is higher than the equilibrium solubility. Within this work the cooling rate during solidification was increased by spray forming flat products, which were hot rolled and tested afterwards.

2. Al-Mg-Sc Alloys

The aluminium-magnesium system is suitable for alloying with scandium, because there are no magnesium-scandium phases in which scandium could be lost for the age hardening Al_3Sc phase. Another positive effect is the increased base hardness by solid solution hardening of the used aluminium-magnesium alloy.

The investigated alloy contained 4.36wt.% magnesium and 0.68wt.% scandium. A known problem of aluminium-scandium alloys is the fast coarsening of the precipitations, which leads to a reduction of hardness and strength.

Davydov et al. [1] show, that additional alloying of low amounts of zirconium leads to the modified $Al_3[Sc_{1-x}Zr_x]$ phase, where zirconium replaces up to 23% of the scandium atoms (Toropova et al. [3]). These modified precipitations have a lower susceptibility for coarsening.

Because of this effect less than 0.1wt% zirconium was given to the alloy. The material was delivered in direct chill (DC) cast billets with a diameter of 50 mm and a length of 500 mm. The chemical composition of the spray formed flat products was checked by optical emission spectroscopy (OES). The content of the alloying elements along the whole flat product was the same than in the direct chill cast base material. There was no segregation found.

3. Spray Forming

The direct chill cast material was molten and sprayed in the spray forming equipment of the collaborative research center 372 of the University Bremen (Herding et al. [4])
The cooling rate during solidification of spray forming is relatively high (100 to 10000 K/s). After solidification the cooling rates in spray formed products are significantly lower (about ~1 K/s). For comparison the cooling rate for direct chill casting is between 1 and 10 K/s for the whole process.

The flat product has been sprayed with the parameters given in Table 1. A relatively high gas to metal ratio (GMR) has been used, to achieve high cooling rates (Freyberg et al. [5]).

Table 1: Parameters of spray forming; substrate velocity: 4 mm/s; laterally scanning spray nozzle.

Melt temperature [°C]	Atomizer gas pressure [MPa]	Tundish Outlet diameter [mm]	Melt flow rate [kg/s]	Gas to metal Ratio (GMR)
838	0.4	4	0.041	8.2

4. Hot rolling of the Flat Products

The flat products dimensions were 500x380x20-30 mm (6 kg); it had different thicknesses along the width. There were two thicker areas approximately 150 mm excentric from the middle of the deposit. This can be seen in the drawing shown below in Figure 1. After spray forming the flat products have a fairly high porosity shown in Figure 1a and 1b. The thinner areas have a higher porosity than the thicker areas. This is the result of the higher heat introduced by more melt in the thicker areas.

For hot rolling, material from between the middle and the thicker areas was used (Figure 1). To prepare the material for hot rolling the very porous layers at the top and at the bottom of the deposit have been milled of. After this the material had a thickness of about 12-14mm. It was hot rolled at temperatures of 350°C, 400°C and 450°C. Rolling was done within 3 steps, each interrupted by 30 minutes in the furnace. The final thickness was approximately 4mm. The deformation degrees of the sheets are shown in Table 2. After hot rolling the density of the sheets was measured by the Archimedes method (Table 2). The measurements for the hot rolled sheets show, that they are almost dense.

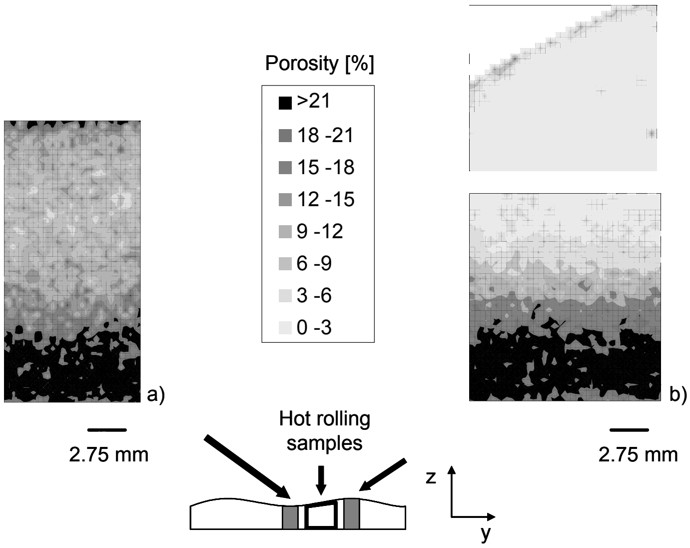

Figure 1a and 1b: Porosity measurements with image analysis; a) thinner region b) thicker region.

Table 2: Deformation degree and density before and after hot rolling.

Rolling temperature [°C]	Deformation degree $\varphi=\ln(d_0/d)$	Density [g/cm³]	Ratio between theoretical and measured density
as sprayed	0	2.294 ± 0.054	0.861 ± 0.020
350	1.1	2.655 ± 0.001	0.997 ± 0.001
400	1.1	2.653 ± 0.004	0.996 ± 0.002
450	1.2	2.641 ± 0.002	0.991 ± 0.001

5. Metallographic Analysis

After hot rolling, micrographs of the spray formed and hot rolled conditions have been compared (Figures 2a and 2b). Both micrographs are from the middle section of the samples. The as spray formed specimen shown in Figure 2a has a lot of pores along the whole micrograph. Opposite, the sheet hot rolled at a temperature of 350°C shown in Figure 2b exhibits nearly no pores. The sheets hot rolled at higher temperatures were dense, too. This was already shown by the density measurements shown in Table 2. The ratio between theoretical density and measured density of the sheets was higher than 99% for all rolling temperatures. This proves, that it is no problem to get compact material out of the spray formed flat products by hot rolling.

To see the grain structure of the hot rolled sheets the micrographs were electrolytically etched (Figure 3). The grain structure was nearly the same for all hot rolling temperatures. In Figure 3, a micrograph of the sheet rolled at 450°C is shown. A fine grain structure and stretched grains can be seen.

This shows, that there was no dynamic recrystallisation during the hot rolling process and no recrystallisation during the time in the furnace between the rolling steps, for all temperatures. Davydov et al. [1] also found no recrystallisation for comparable aluminium-magnesium- scandium alloys at those temperatures.

Transmission electron microscopy images were taken to investigate the microstructure with higher resolutions. In Figure 4a an image of the very fine subgrain structure can be seen. This subgrain structure cannot be seen by light microscope because of the low subgrain size and the used etching method, which can just distinguish wide-angle grain boundaries.

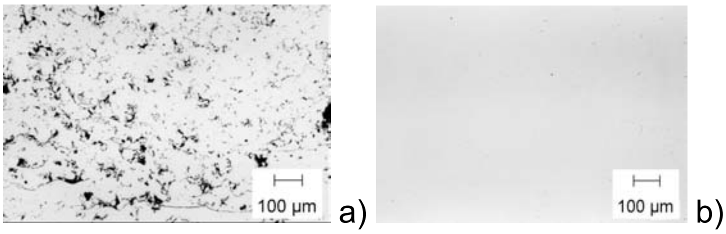

Figure 2: Microstructures of a) spray formed state b) hot rolled state (350°C); both not etched.

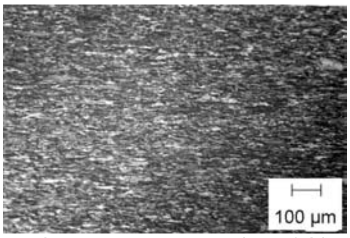

Figure 3: Microstructure of hot rolled state (450°C); electrolytically etched.

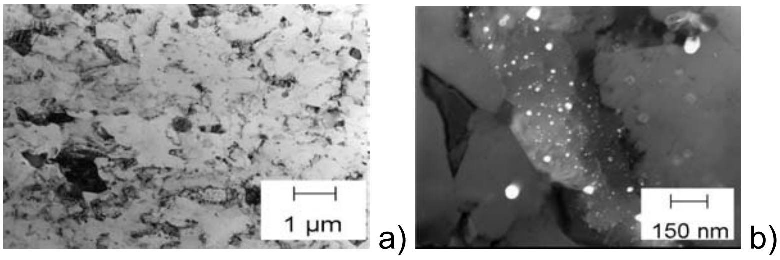

Figure 4: Microstructure a) bright field TEM image b) dark field TEM- image of one subgrain.

The secondary $Al_3[Sc_{1-x}Zr_x]$ precipitations can be seen by transmission electron microscopy in Figure 4b. The photograph is a dark field image, from a reflex of the $L1_2$ structured $Al_3[Sc_{1-x}Zr_x]$ precipitations. This reflex is only valid for one subgrain, so that the precipitations can be seen in just this subgrain with a width of about 300 nm and a length of about 1.5 µm. The average precipitation size seen in Figure 4b is less than 10 nm.

6. Mechanical Properties

Tensile tests were performed at room temperature with specimens according to the German standard DIN 50125 E 3x8x30. All specimens were taken in longitudinal direction of the sheets. The mechanical properties of the hot rolled sheets were tested by Brinell hardness and tensile tests. In Table 3 and in Figures 5, it can be seen, that the hardness and the 0.2% yield strength of the sheet hot rolled at 350°C is highest with the values of 128±1 HBS2.5/62.5 and 336±8 MPa.

Table 3: Mechanical Properties before and after hot rolling.

Rolling Temperature [°C]	Hardness [HBS 2.5/62.5]	0.2%-Yield strength [MPa]	Ultimate tensile strength [MPa]	Ultimate Strain [%]
as sprayed	77 ± 1	-	-	-
350	128 ± 1	337 ± 8	385 ± 25	6 ± 4
400	118 ± 1	309 ± 4	398 ± 7	15 ± 1
450	108 ± 2	294 ± 5	352 ± 30	7 ± 4

The hardness and the 0.2%-yield strength of the sheets rolled at higher temperatures are lower. This could have two reasons. First, these sheets could be over aged. It is well known [1,3,6-8], that higher temperatures lead to overaged condition after shorter aging times. Second, at higher temperatures less work hardening could remain in the sheets. The tensile tests showed, that the ultimate strain was highest for the sheet hot rolled at a temperature of 400°C. This could be an effect of higher density. The samples hot rolled at 350°C and 450°C may include a few isolated pores, which reduce ultimate strain.

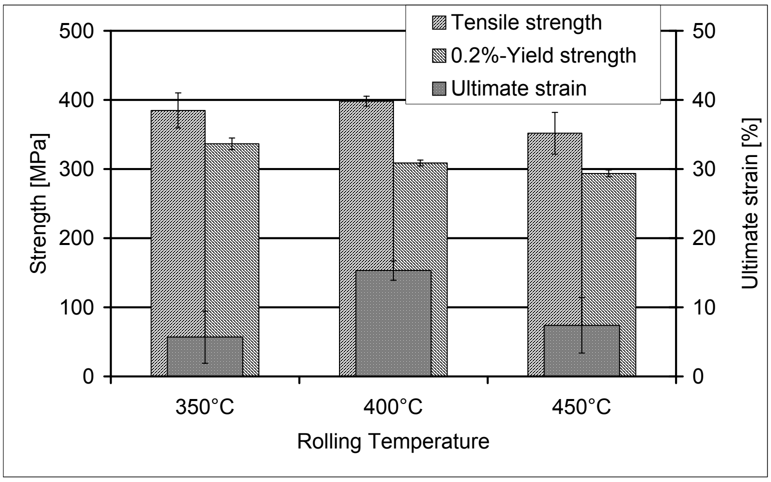

Figure 5: Tensile properties of the hot rolled sheets.

7. Summary

It was possible to densify produce a spray formed aluminium-magnesium-scandium flat product by hot rolling at 350-450°C. This was shown by density measurements and micrographs of the as sprayed and hot rolled state. The analysis of etched micrographs from different rolling temperatures showed no recrystallisation in the microstructure. The hardening phase $Al_3[Sc_{1-x}Zr_x]$ was shown by TEM dark field images. The hardness measurements and the tensile tests showed, that the sheet hot rolled at 350°C achieved the highest hardness and 0.2%-yield strength. But the sheet hot rolled at 400°C showed the highest elongation.

Acknowledgements

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