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Optimisation of the Strength of Aluminium Foam Sandwich (AFS) Panels by Different Heat Treatments

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Abstract. Aluminium foam sandwich panels (AFS) made of a low-density aluminium alloy AlSi6Cu6 foam core and two dense 6082 alloy face sheets were fabricated, after which the panels were subjected to two different heat treatments. First, the AFS panels were aged to increase their strength without further solution heat treatment and fast quenching, a process which resembles a T5 treatment. Second, to define a reference point the face sheets of AFS samples were cut off the foam and subjected to a full T6 treatment. Hardness profiles were measured across the thickness of the face sheets after the two different treatments and the microstructure was investigated. The main conclusion is that mechanical performance of AFS panels can be considerably increased by heat treatment without full solution heat treatment (T5), but without reaching the level of a full T6 treatment. The potential use of an easy to apply T5 treatment is an important cost reducing factor.

Introduction

Aluminium foam sandwich (AFS) materials are structures comprising two layers of dense aluminium alloy sheets and a core of aluminium foam in between. The AFS manufacturing process [1] allows for a flexible combination of materials (face and core), sample dimensions (up to 3 m^2 area, up to 40 mm thickness) and shapes (flat or curved). AFS properties such as low density, high mass-specific stiffness, good impact resistance, high energy absorption capability lead to real and potential applications in automotive industry, in aerospace technologies and for mechanical engineering.

The sheet material used for the AFS compound in the current study is a 6082 alloy. The strength of 6xxx series alloys is mainly caused by very fine precipitates, containing both Mg and Si, embedded in a solid solution matrix. Age hardening is crucial to achieve good performance. Precipitation formation and precipitation sequence [2-4], the correlation between hardness and microstructure [2, 5,6], quantitative analyses of early stage precipitates and clusters [2, 6-8] and precipitate evolution after isothermal heat treatment [9] have been investigated thoroughly during the past years.

An optimisation of AFS sheet material with respect to its mechanical properties is the aim of this work. Age hardening of both the face sheets and the foam core is an obvious way to increase performance. The problem is that AFS cannot be water quenched after solutionising to allow for subsequent ageing to T6 since such quenching can damage both the foam – due to intruding water - and the face sheets which can deform due to the differences in thermal behaviour between skins and core. We concentrate on hardening of the face sheets and try to evaluate whether direct ageing after fabrication which can be thought to produce a certain degree of supersaturation provides an increase in hardness. We study the effect of diffusion of elements from the foam core into the face sheets which changes chemical composition locally.

Experimental

Aluminium foam sandwich panels (AFS) made of a low-density AlSi6Cu6 foam core and two dense 6082 face sheets – composition Al-1.2 Mg-1.3 Si-1.0 Mn (in wt.%) – were fabricated. For this a sheet of the foamable alloy - which had been made by solidifying powder mixtures including titanium hydride acting as blowing agent - was deformation-bonded to two 6082 alloy sheets to form a three layer composite. The composite was foamed by heating to 590°C allowing the core to expand up to 8 to 11 times the original volume while the face sheets remained solid. After reaching maximum expansion the AFS was air cooled. Fig. 1 defines the configuration.
After cooling the AFS panels were aged at 185°C for up to 20^h to increase their strength without further solution heat treatment and fast quenching (T5 condition). To define a reference point the AFS face sheets were also subjected to a full T6 treatment: solution treatment at 510°C for 8^h; quenching into water at room temperature and ageing at 185°C for up to 3^h. Micro-hardness measurements were carried out on sectioned specimens perpendicular to the face sheets by averaging 5 measurements for each point. Microstructure was characterized by light microscopy and by a Philips CM30 TEM operated at 300 kV. Thin foils suitable for TEM investigations were prepared by electrochemical jet polishing using HNO_3-CH_3OH electrolyte.

Results and Discussion

As-fabricated AFS (no heat treatment)

Fig. 1 shows an AFS structure as used in this study. The microstructure of a region of this AFS sheet exhibiting two different areas is shown in Fig. 2. The corresponding micro-hardness profile as a function of distance from the surface of the sheet alloy is presented in Fig. 3. Starting from the surface the micro-hardness is almost constant for about 1.40 mm, with an average of 57.9 HV. Within further 0.4 to 0.5 mm a strong increase of micro-hardness to about 94 HV is observed. Corresponding to the microstructure two different micro-hardness regions can be identified. We call the sheet layer the "*metallic zone*", the heterogeneous zone close to the interface to the foam formed after rolling and foaming of the AFS sample the " *diffusion zone*".

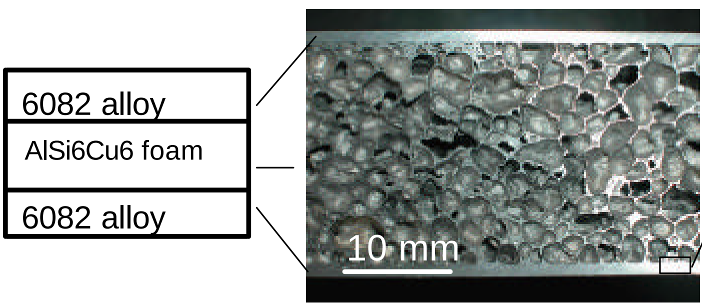


Fig. 1 AFS before (left) and after fabrication (right). Optical image (right) of as-fabricated AFS specimen. Dense 6082 alloy sheets and foamed AlSi6Cu6 alloy core can be seen.

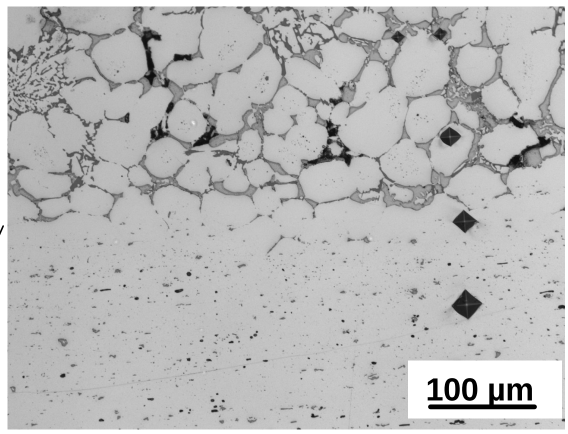


Fig. 2 Optical micrograph of microstructure of AFS 6082 sheet showing a metallic zone (bottom) and a diffusion (top) zone.

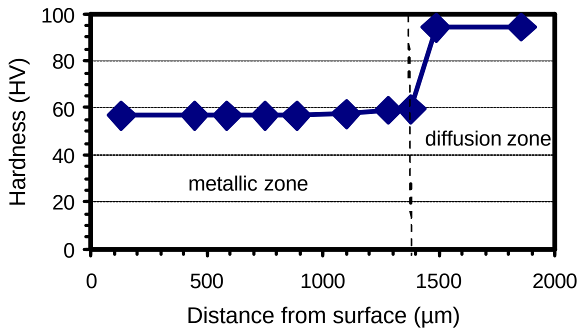


Fig. 3 Vickers micro-hardness evolution as a function of the distance from the surface of the sheet of the as fabricated AFS specimen. .

In Fig. 4 a TEM micrograph and the corresponding selected area electron diffraction (SAED) pattern obtained from the metallic zone is given. The [001] SAED image of the aluminium matrix shows additional diffraction patterns which originate from the precipitates. In the bright field image (fig. 4) these needle-like or rod-shaped precipitates are imaged by dark contrasts. The elongated precipitates are always aligned to one of the <100> Al directions. Both kind of precipitates are longer than 500 nm, with a dimension in cross-section ranging from about 30 nm to 200 nm. Another kind of precipitate was observed in the diffusion zone, differing from the precipitates in the metallic zone by morphology and size as can be seen in Fig 5. The [001] SAED image of the Al matrix also shows additional diffraction patterns which are generated by the precipitates in this area. Diffraction patterns from these precipitates are very similar to those in Fig. 4. In order to clarify the differences between these two kinds of precipitates, more investigations are necessary. However, this difference in microstructure of the metallic and diffusion zones is clearly correlated with the changes of the micro-hardness.

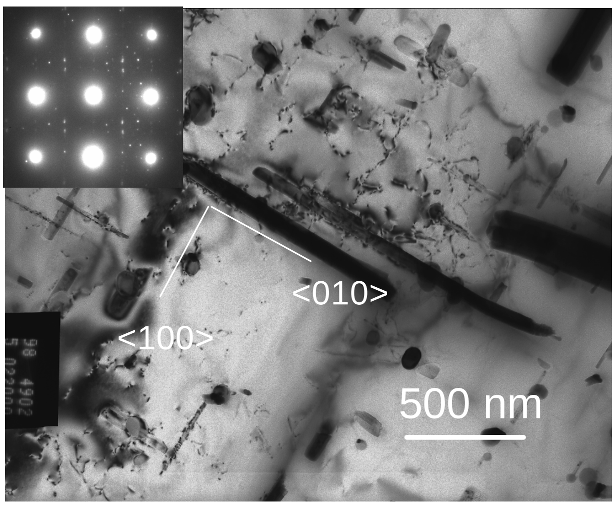


Fig. 4 Bright field TEM image of 6082 sheet in as-fabricated AFS alloy (metallic zone). The corresponding [001] zone axis of SAED pattern of Al matrix is given in the inset.

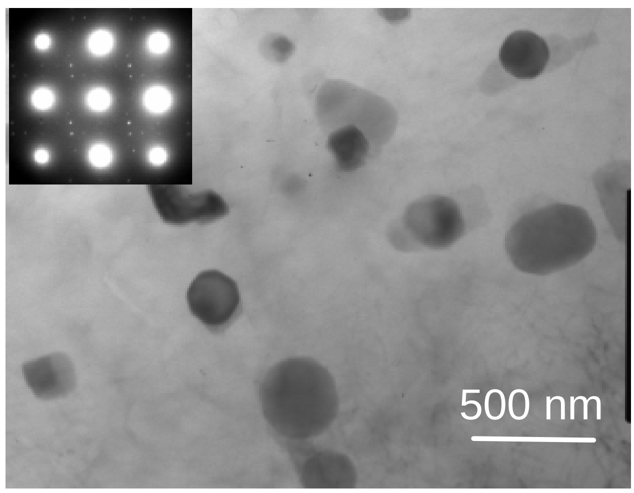


Fig. 5 same as Fig. 4 but diffusion zone.

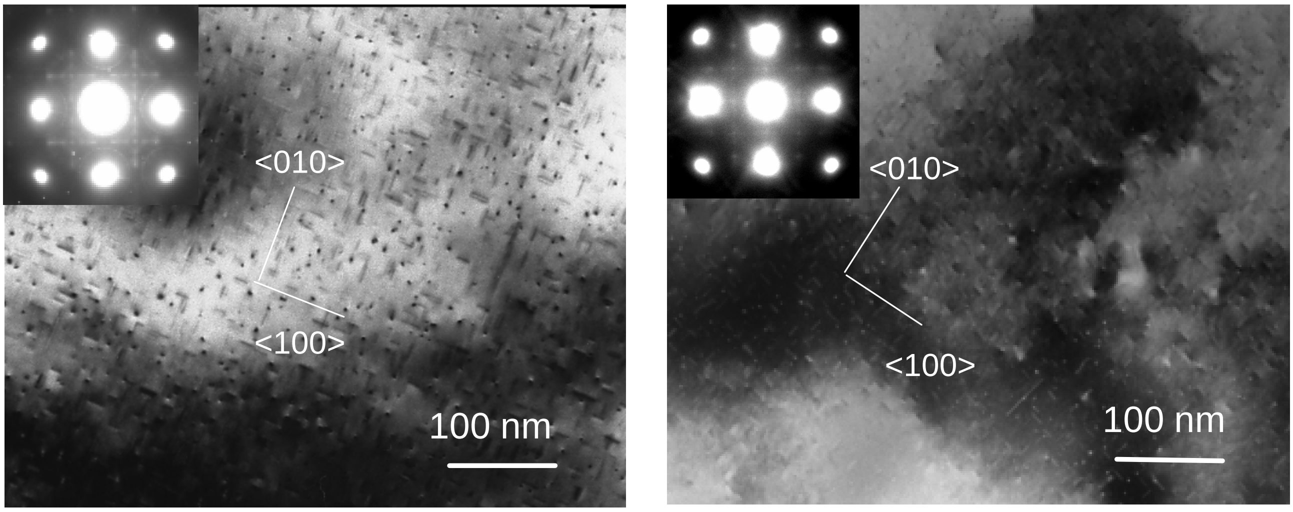
Artificial ageing to T6

Table 1 presents results of micro-hardness measurements in the three regions of the AFS sheet after different ageing times. Maximum hardness in the metallic zone (115.2 HV was reached after 1.5^h.

Time of Ageing (hour)	Metallic Zone	Close to Diffusion Zone	Diffusion Zone
after solutionising	51.0	60.2	83.7
1.5	115.2	125.3	130.4
2.0	114.4	129.8	135.0
3.0	105.8	125.8	134.0

Table 1: Vickers micro-hardness (HV) of 6082 face sheets of AFS in solution heat treated and artificially aged (185°C) T6 conditions. Solutionising was carried out at 510°C/8^h with subsequent quenching in water.

Figures 6 a) and b) show TEM bright field images of microstructures in both the metallic and the diffusion zone after solutionising at 510°C/ 8^h, quenching in water and subsequent ageing at 185°C for 1,5^h. Both micrographs were obtained in the [001] orientation of the Al matrix. Ageing at 185°C produces small needle-shaped precipitates. In addition, streaks along the [001] directions are observed in the SAED patterns. These streaks are from needle-shaped precipitates aligned to one of the <100> Al directions and are attributed to the β'' phase [2]. The length of the precipitates is about 22 nm in the metallic zone. In the cross-section they are approximately spherical. Hardening of the alloy is mainly caused by such very small precipitates embedded in a solid solution matrix.



a) b)

Fig. 6 BF TEM images of the microstructure and corresponding <001> SAED pattern of 6082 face sheet in AFS specimen after solutionising at 510°C/ 8^h, quenching in water and subsequent ageing at 185°C for 1,5^h; a) metallic zone and b) diffusion zone.

Several investigations of precipitation in Al-based alloys were carried out by 3-dimensional atom probe (3DAP) [2,3,6,8]. It was found that the precipitates are rich in Mg and Si. The number density of precipitates depends on the Mg and Si content. In Si-excess alloys the number density of precipitates was found to be higher than in the balanced alloy (Mg/Si = 2) [8]. Precipitates observed in the diffusion zone are smaller than those observed in the metallic zone as shown in Fig. 6b. Careful observations of the microstructure indicate that the small precipitates are also very thin needles. They are probably rich in Mg and Si. The average length of needles is about 12 nm which is lower than the length of precipitates (22 nm) in the metallic zone. As the foam alloy contains 6 wt.% of Si, it can be expected that more than 1.3 wt.% Si (as contained in 6082) is contained in the diffusion zones of the face sheet alloy. Thus, the number density of such small precipitates in the diffusion zone is possibly increased as compared with that in the metallic zone. The density and size of precipitates are related to the macroscopic mechanical properties of the alloy as can be seen in Table 1. The influence of Cu on precipitation in the diffusion zone could not be resolved in this investigation. Further experiments by 3DAP are necessary.

Effect of T5 Heat Treatment of as Fabricated AFS Specimen

Micro-hardness as a function of the ageing time at 185°C for as-fabricated samples are presented in Fig. 7. The increase of micro-hardness with ageing time is significant. After 8^h ageing at 185°C the micro-hardness has a value of 87.7 HV corresponding to a 51.5 % increase in micro-hardness compared to that of as-fabricated sample (57.9 HV) although no solution heat treatment nor quenching was carried out.

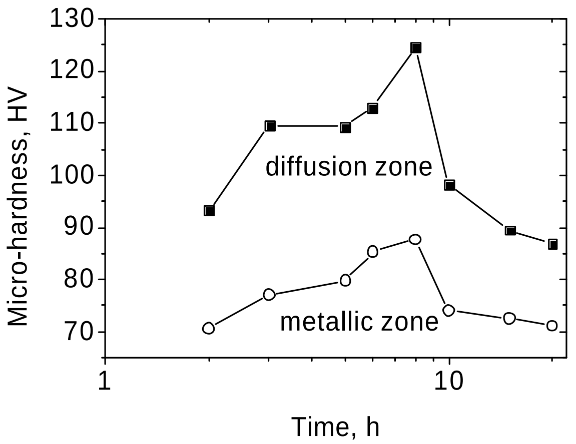


Fig. 7. Vickers micro-hardness of 6082 sheet in AFS at T5 condition.

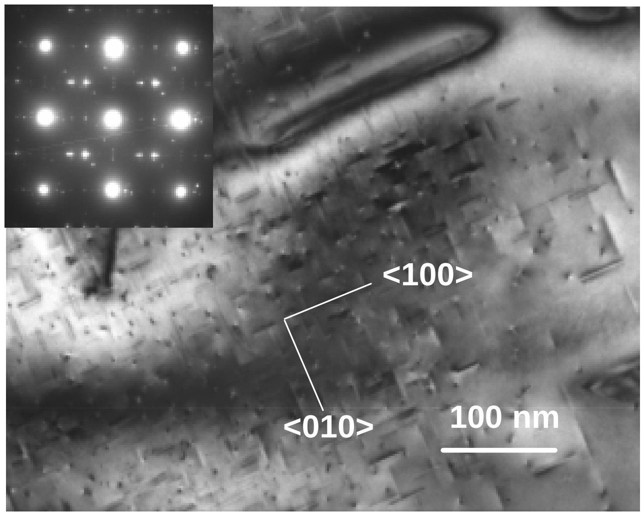


Fig. 8 BF TEM image of 6082 face sheet and corresponding <001> SAED pattern after ageing at 185°C for 5^h (metallic zone).

A typical BF TEM image of the metallic zone after ageing at 185°C for 5^h is shown in Fig. 8. Beside the large rod-like precipitate with an average length >300 nm, small needles were observed after this heat treatment. The average length of the needles is about 25 nm. The observed micro-hardness for this specimen is about 80 HV. This value is much smaller as compared to 106 HV of specimens aged under T6 conditions for 3^h. Although the needles have comparable sizes in T6-aged specimens after 3^h and T5 after 5^h, a decrease of micro-hardness for T5 after 5^h was observed. This observation can be explained by the presence of large rod-like precipitates which decrease micro-hardness.

Summary

Aluminium Foam Sandwich (AFS) material was investigated in different conditions:

1. as-fabricated: final product of AFS which is currently processed in the industry.
2. face sheet artificially aged to T6: a) solutionised at 510°C for 8^h, b) quenched in water at room temperature, and c) aged at 185°C for 1.5^h, 2^h and 3^h.

3. AFS, T5-heat treated: aged at 185°C up to 20^h without any solutionising and quenching.

Fig. 9 shows the highest micro-hardness of samples after a given heat treatment. The highest hardness of 115.2 HV was obtained in the T6 condition (obtained on a bare face sheet from which most of the foam had been removed). For the case where solutionising and quenching was omitted (T5 condition) a hardness of about 88 could be obtained. Therefore, T5 can increase hardness of the sheet by about 51.5 % compared to the as-fabricated condition (57.8 HV) which is used at present.

T5 treatment was shown to deliver an increase in hardness which, although it is modest compared to full T6 treatments, is significant. The advantage is that T5 is feasible for aluminium sandwich structures unlike T6 which involves water quenching.

A future tailoring of the cooling conditions after fabrication could help increasing supersaturation and deliver even higher hardness values in the T5 condition. Moreover, the potential of hardening the foam core has to be evaluated. Related studies exist for bare foams without face sheets only [10].

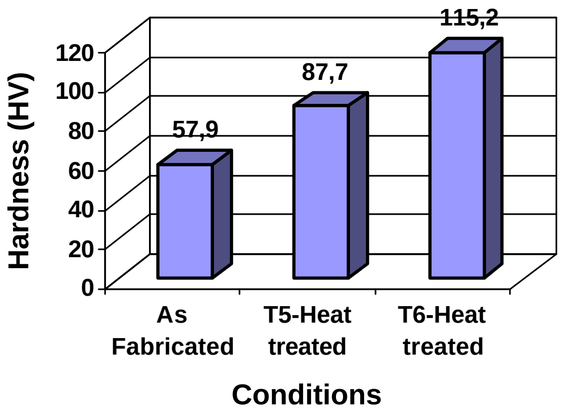


Fig. 9 Micro-hardness as a function of different heat treatment conditions in the metallic zone of 6082 face sheet of an AFS.

Acknowledgments
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