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Influence of $\text{Al}_3(\text{Sc,Zr})$ Precipitates on Deformability and Friction Stir Welding Behavior of Al-Mg-Sc-Zr Alloys

Johannes Taendl and Cecilia Poletti

Institute of Materials Science and Welding, Graz University of Technology, Graz, Austria

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Abstract: We investigate the influence of $\text{Al}_3(\text{Sc,Zr})$ precipitates on the cold deformability and friction stir welding behavior of a novel AlMg4Sc0.4Zr0.12 alloy. To analyze the influence of the precipitate state on the flow stress, samples were pre-aged at various temperatures for up to 120 min prior to plane strain compression. It was found that the flow stress increased considerably with increasing pre-ageing temperature and duration. The formation of $\text{Al}_3(\text{Sc,Zr})$ precipitates during friction stir welding was investigated on welds with high and low heat input by measuring the respective hardening response with and without post-weld heat treatment.

Keywords: Al-Sc alloys, Cold deformation, Friction stir welding

Einfluss von $\text{Al}_3(\text{Sc,Zr})$ Ausscheidungen auf Umformbarkeit und Reibrührschweißverhalten von Al-Mg-Sc-Zr Legierungen

Zusammenfassung: Wir untersuchen den Einfluss von $\text{Al}_3(\text{Sc,Zr})$ Ausscheidungen auf das Kaltumform- und Reibrührschweißverhalten einer neuartigen AlMg4Sc0.4Zr0.12 Legierung. Um den Einfluss des Ausscheidungszustandes auf die Fließspannung zu analysieren, wurden Proben vor dem Kaltstauchen bei verschiedenen Temperaturen bis zu 120 min vorausgelagert. Die Fließspannung nahm deutlich mit zunehmender Auslagerungstemperatur und -zeit zu. Die Entstehung von $\text{Al}_3(\text{Sc,Zr})$ Ausscheidungen während des Reibrührschweißens wurde an Schweißungen mit hohem und niedrigem Wärmeeintrag untersucht, indem die jeweilige Härte mit und ohne Nachwärmebehandlung gemessen wurde.

Schlüsselwörter: Al-Sc Legierungen, Kaltumformung, Reibrührschweißen

1. Introduction

The civil aircraft market showed a considerable growth over the last centuries and is expected to substantially grow in the near future (Fig. 1). The evolution of the civil aircraft industry is put into numbers in Fig. 1 (a) by means of the worldwide annual revenue-passenger kilometers (RPK), i.e. the total number of air kilometers travelled by paying customers. According to this forecast, the RPK will double in the next 20 years leading to an increasing need for civil aircrafts, in particular single-aisle types. It is expected [1] that there is a total need for around 23,000 single-aisle aircrafts until 2034, which, in consequence, leads to a significant need for structural materials (Fig. 1b).

When considering the weight fraction of materials used in Airbus aircrafts over the last 50 years, Al-alloys were the dominant material until the latest twin-aisle aircraft A350 launched in 2014 (Fig. 2). Despite the increased use of composite materials at the expense of Al-alloys for new long-range aircrafts, an identical development is not expected for single-aisle aircrafts, as stated for example in [2]. For fuselage components in short-range aircrafts, for example the Airbus A320, it is assumed that the weight reduction achieved by using expensive composite materials instead of Al-alloys is not profitable. An Al-based fuselage design is therefore expected. However, the currently used Al-Cu alloys are intended to be replaced by alloys with improved weldability and corrosion performance, such as Al-Mg-Sc alloys.

2. Alloying Concept Al-Sc

Conventional AlMg alloys possess good work-hardenability, welding characteristics, and corrosion resistance, but only limited strength compared to age hardening high-

J. Taendl (✉)
 Institute of Materials Science and Welding,
 Graz University of Technology,
 8010 Graz, Austria
 E-Mail: johannes.taendl@tugraz.at

Fig. 1: Development and forecast of the annual worldwide revenue-passenger kilometers (RPK) until 2034 (a) and forecast of total sales for single-aisle, twin-aisle, and very large aircrafts until 2034 (b) [1]

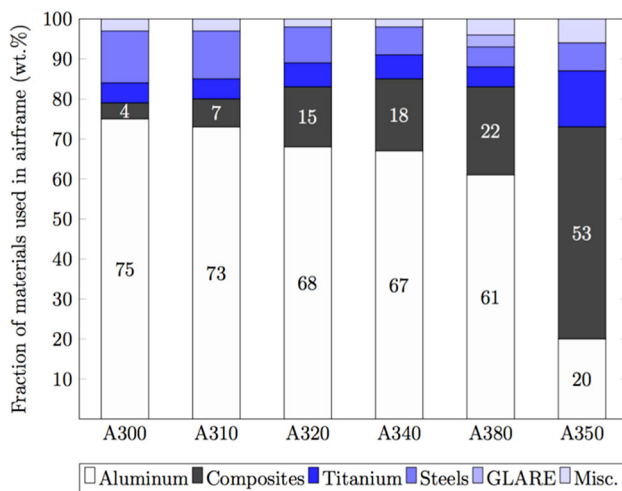
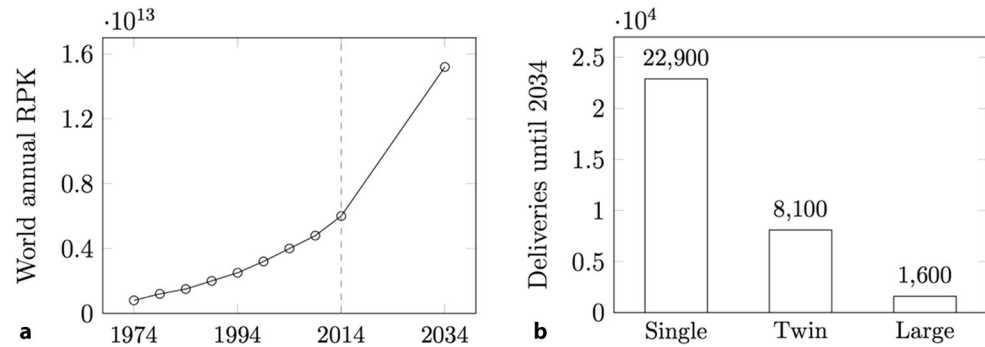


Fig. 2: Material mix used in Airbus planes over around 50 years from A300 (1972) to A350 (2014). Data kindly provided by Airbus Group Innovations

strength Al-alloys such as AlCu [3]. In order to increase the specific strength of AlMg alloys while maintaining the beneficial materials properties, the balanced addition of small amounts of scandium and zirconium is considered as one of the most promising approaches [4].

The dominant metallurgical system for AlMgScZr alloys with technically relevant chemical compositions [5], i.e. less than 6 wt.% Mg, 1 wt.% Sc and 0.5 wt.% Zr, is the Al-rich side of the binary system Al-Sc, illustrated schematically in Fig. 3 (a). For an alloy that follows the Al-Sc system, the materials properties strongly depend on the presence and nature of the equilibrium phase Al_3Sc . If Al_3Sc forms

as precipitates from a supersaturated solid solution, considerable strengthening can be achieved. In addition, the precipitates efficiently stabilize a deformed, strain hardened microstructure. The Al_3Sc precipitation potential with all its benefits is, however, limited by the low solubility of Sc in Al. The solid solubility limit in Fig. 3 (b) demonstrates a maximum solute Sc-concentration of as little as 0.1 wt.% at 550 °C, which increases only to 0.4 wt.% at 660 °C. The addition of Mg and Zr to AlSc alloys further decreases the maximum Sc solubility [6]. However, these elements are needed for solid solution strengthening in case of Mg and to form more thermally stable precipitates of the type $\text{Al}_3(\text{Sc,Zr})$ in case of Zr. Owing to the difficulties of a solution treatment close to melting temperature, a high degree of Sc supersaturation in AlMgScZr alloys is practically only achievable using direct chill casting processes with high solidification and cooling rates.

In this work, we show the influence of $\text{Al}_3(\text{Sc,Zr})$ precipitates induced by different heat treatments on the cold deformability of a rapidly solidified Al-Mg-Sc-Zr alloy as well as the friction stir welding behavior of the material. In this way, we analyze the behavior of the alloy under different possible processing routes.

3. Material

The investigated material was an AlMg4Sc0.4Zr0.12 alloy casted to an 8 mm thick, 280 mm wide, and 30 m long strand using a continuous belt-casting technology. We have shown that, due to the solidification conditions, 0.13 \pm 0.02 wt.% Sc of nominal 0.4 wt.% was in solution in as-

Fig. 3: Schematic illustration of the Al-rich region of the Al-Sc phase diagram (a) and solubility of Sc in solid Al as a function of temperature (b) [6, 7]

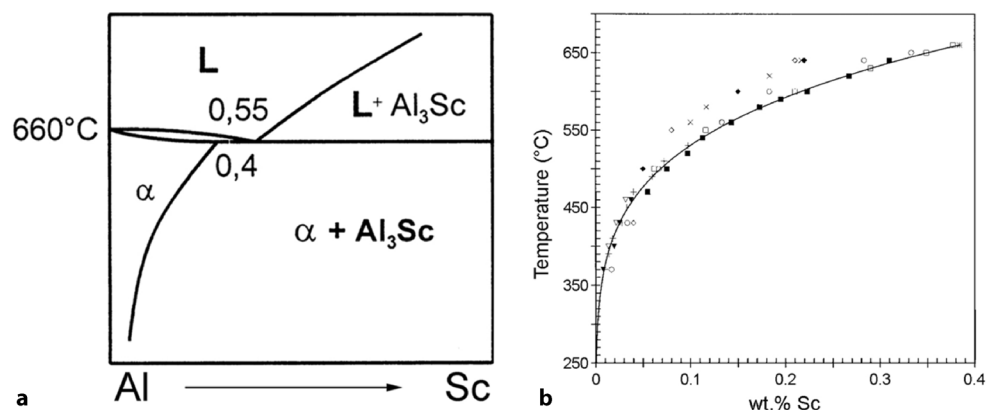
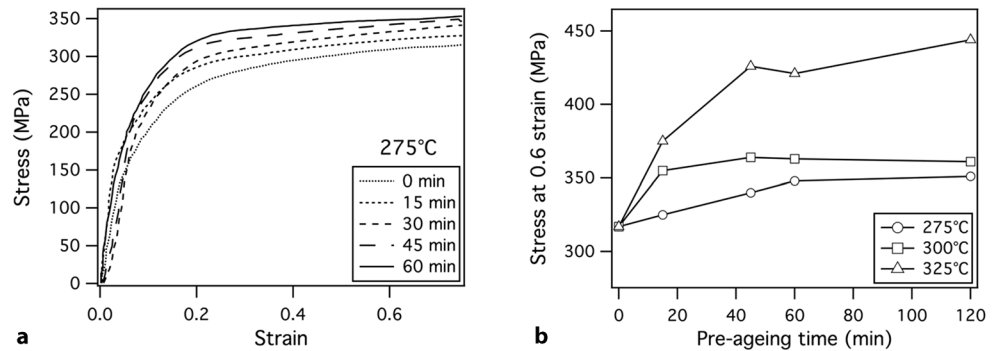


Fig. 4: Influence of the duration of pre-ageing at 275 °C on the stress-strain curves during compression (a) and summary of the flow stresses at 0.6 strain for various pre-ageing conditions (b)



cast (AC) condition. Using an electron-beam re-solidification (EBRS) process, where the material is remelted and rapidly solidified, the solute Sc-content was increased to 0.37 ± 0.03 wt.% [8, 9]. For the studied material, we have demonstrated significant hardening due to precipitation of $\text{Al}_3(\text{Sc,Zr})$ particles. It was shown that hardening was more pronounced in case of EBRS compared to AC condition as a result of a higher number density of coherent precipitates with radii between 3 and 5 nm [9]. Furthermore, the formation of the $\text{Al}_3(\text{Sc,Zr})$ precipitates during ageing of a cold deformed microstructure led to considerable Zener pinning and a stop in recrystallization [10]. This effect was so pronounced that full recrystallization was not observed within 60 min even at temperatures as high as 500 °C [11]. In addition, we showed that precipitates influenced the materials behavior during hot deformation [12].

Based on the outcome of the fundamental investigations mentioned above, the present study shows more practical aspects of the complex interactions occurring during processing of the given $\text{AlMg}_4\text{Sc}_0.4\text{Zr}_0.12$ alloy. In particular, we investigate the influence of $\text{Al}_3(\text{Sc,Zr})$ precipitates on the cold deformability and friction stir welding behavior.

4. Experimental Methods

The cold deformation behavior was studied in plane strain condition using a Gleeble 3800 Hydrowedge system (DSI). Samples with a size of $10 \times 20 \times 4$ mm (L x W x T) were compressed to 0.8 equivalent strain with a strain rate of 1 s^{-1} . To analyze the influence of the $\text{Al}_3(\text{Sc,Zr})$ precipitate state on the flow stress, the AC samples were pre-aged at 275 °C, 300 °C, and 325 °C for up to 120 min prior to deformation.

Friction stir welding (FSW) of AC material was carried out using an ISTIR FSW machine (MTS). Blind welds were accomplished on 8 mm thick belt-casted material using a threaded-pin tool (Stirtec) with a shoulder diameter of 15 mm and a pin length of 5.5 mm. The basic process parameters were a tilt angle of 0° and a tool rotation speed of 1200 min^{-1} . We studied the hardening response of the material due to high heat input (100 mm/min feed rate) and low heat input (1000 mm/min feed rate) as well as the influence of a post-weld heat treatment (PWHT) at 325 °C for 60 min.

5. Results and Discussion

5.1 Deformation Behavior

Fig. 4 (a) shows flow curves of samples pre-aged at 275 °C between 0 and 60 min. The flow stress increased with increasing pre-ageing time. This effect was even more pronounced for higher ageing temperatures and longer times, as shown in Fig. 4 (b). Based on our studies on the $\text{Al}_3(\text{Sc,Zr})$ precipitation kinetics [9], we attribute the increasing flow stress to particle-dislocation interactions occurring during deformation. If annealing follows cold deformation of non pre-aged material, we have shown that $\text{Al}_3(\text{Sc,Zr})$ precipitation occurs simultaneously with static recrystallization. Despite the Zener pinning effect exerted by the growing particles, a fraction of recrystallized grains is present after some time leading to softening [11]. The present processing route consisting of pre-ageing followed by cold deformation thus leads to higher final strength than the one in reversed order.

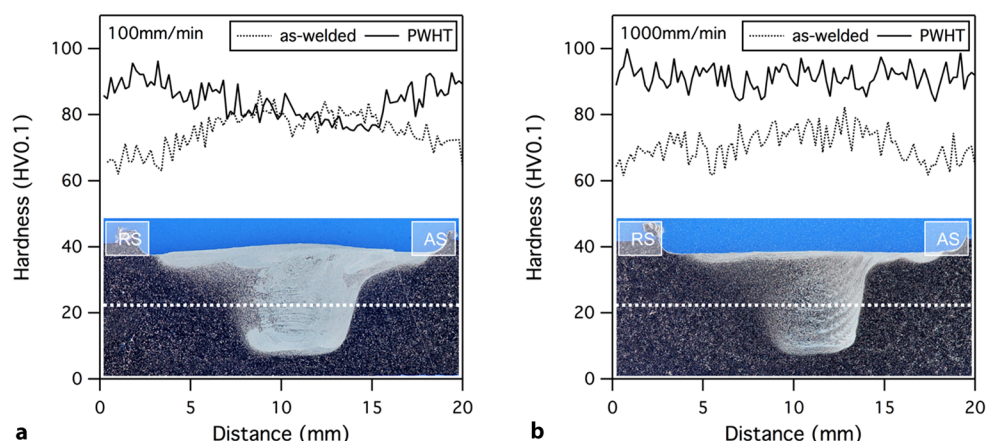
5.2 Friction Stir Welding

Fig. 5 shows macrosections and hardness patterns across the welds for high heat input (a) and low heat input (b). The dashed lines represent the as-welded condition while the full lines show the hardness after PWHT at 325 °C for 60 min. In case of high heat input (a), the hardness in the weld zone increased slightly in as-welded condition, whereas the maximum hardness of the base material could not be reached after PWHT. In case of low heat input (b), the hardness in the weld zone did not increase considerably in as-welded condition. After PWHT, however, the maximum hardness of the base material was reached. We concluded that, for low heat input, $\text{Al}_3(\text{Sc,Zr})$ precipitates formed already during welding at temperatures higher 325 °C, which was not the case for lower heat input because of shorter exposure to high temperatures. During PWHT at 325 °C, therefore, additional precipitation hardening was only achieved in the weld zone of the low heat input weld.

6. Summary

In this study we have shown the influence of $\text{Al}_3(\text{Sc,Zr})$ precipitates on the cold deformation and friction stir weld-

Fig. 5: Macrosections and hardness curves for high heat input (a) and low heat input (b) welds showing the influence of the welding parameters on the $Al_3(Sc,Zr)$ precipitation



ing behavior of a novel belt-casted $AlMg_4Sc_0.4Zr_0.12$ alloy. The flow stress during cold deformation increased with increasing pre-ageing temperature and time. For friction stir welds, the maximum hardness in the weld zone was achieved by low heat input welding combined with a PWHT.

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