CREEP FORMING OF AlMgSc ALLOYS FOR AERONAUTIC AND SPACE APPLICATIONS

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Abstract

New AlMgSc alloys have been developed for the Airbus A380. These alloys have many advantages but demonstrate poor formability at room temperature.

An investigation into the creep forming process was performed at the EADS CRC Germany in order to find a forming solution. The metallurgical properties of AlMgSc alloys mean that it is possible to form components at higher temperatures than those commonly used for age creep forming of 2XXX, 6XXX and 7XXX components. The process can only work below 473 K (200°C) in the family of age hardenable alloys. The residual stresses cause the panel to spring back in this temperature region. In order to compensate for this phenomenon, a computer simulation of the spring-back is necessary to calculate the shape contours of the component.

At approximately 573 K (300°C), the properties of AlMgSc alloys do not deteriorate and after creep forming, spring-back does not occur due to stress relaxation. Manufacture of aircraft fuselage sections with these AlMgSc alloys combined with advanced creep forming technology is much more efficient than the traditional method.

1 Introduction

Airbus Industries want to build a new large aircraft called the A380 to meet the requirements of increased air traffic. This aircraft could transport between 500 and 700 people and would have two decks. New joining processes (such as laser beam welding (LBW), friction stir welding) and aluminum alloys have been developed with the aim of reducing production costs, fuel consumption and maintenance. The LBW process consists of welding the stringers to the panels instead of riveting them. This would cut manufacturing costs and also reduce the weight of the fuselage. But the use of this joining process necessitates development of new alloys (or modification of existing alloys). The requirements for these new alloys are:

- low density
- good combination of strength and toughness
- good weldability
- high corrosion resistance

The AlMgSc alloys from the 5XXX series are some of the new aluminum alloys that have been developed. These materials have the required properties, but unfortunately the stretch forming method commonly used by Airbus to form fuselage shells with double curvature does not work with these alloys. In fact, cracks occur in the sheet metal near the clamping tools. The creep-forming process has been investigated with a view to solving this problem.

2 Principle of creep forming

2.1 Age creep forming

This process consists of restraining a component to a specific shape during heat treatment, allowing the component to relieve stresses and creep to contour [3-6].

The panel consists of a sheet metal that is applied to the die. A plastic foil covers the panel and is bonded onto the die. The air between the plastic foil and the die is pumped out. The vacuum means that the resultant shell fits the contour of the forming tool. All these elements are placed in the autoclave and heated. The forming temperature and time depend on the alloy. The stresses arising inside the shell relax until the shell is cooled and the pressure is removed, but the stresses inside the panel do not completely disappear. These residual stresses lead to spring-back in the part at the end of the forming process and currently represent the main problem in creep forming (figure 1). The temperature and radiuses of the shape play a key role: they determine the speed of forming and the level of stress inside the panel before the temperature decreases.

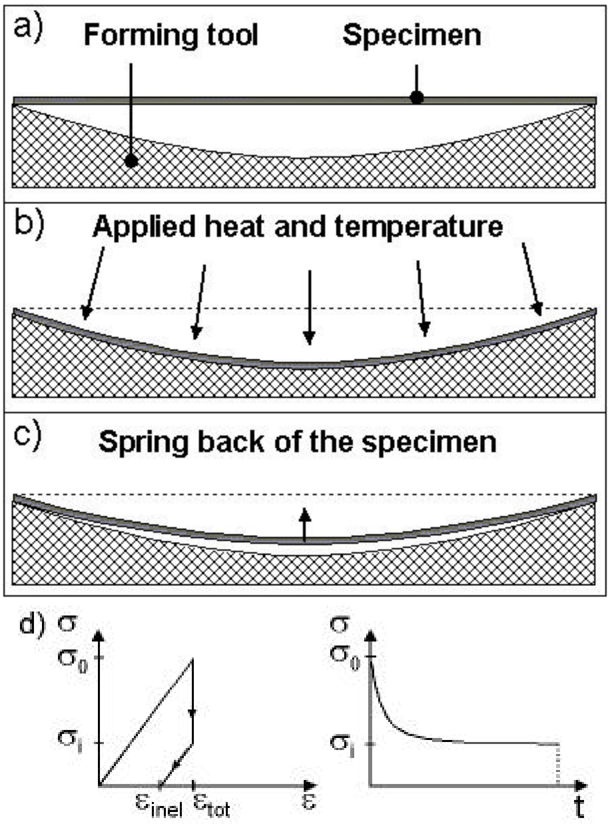

Figure 1: Principle behind the creep-forming process: a) sheet metal placed in the die; b) vacuum, pressure and heat are applied; c) residual stresses make the shell spring back; d) diagram showing stress relaxation that occurs during creep forming [5]

In the case of age-hardenable alloys, the temperature and duration of the process control precipitation hardening. This in turn defines the mechanical properties of the part. The forming temperature must be lower than 473 K (typically 448 K), because temperatures in excess of this would cause the alloy to age and exhibit degraded properties.

2.2 Creep forming in non-age-hardenable alloys

The forming temperature can be higher in the case of non-age hardenable alloys like AlMgSc, if the chemistry and microstructure of the alloy allow this. Two factors operate in the case of AlMgSc alloys and 5XXX alloys. The longer the alloy remains at a temperature between 423 K to 473 K, the more sensitive it is to corrosion, but the temperature must be below the range 573 K - 623 K in order to effect forming without greatly reducing the mechanical properties of the alloy obtained through cold rolling. An explanation of why AlMgSc alloys are particularly interesting for the application of creep-forming is given below.

3 Experimental results

3.1 Properties of AlMgSc alloys at elevated temperatures

3.1.1 Thermal stability of AlMgSc alloys

The thermal stability of two AlMgSc alloys was studied and the results are presented in figure 2. This figure shows that heat treatment only has a minimal effect on the mechanical properties of alloys. The effect of heat treatment is observed above a temperature of about 573 K. The small decrease in the values at 473 K is not significant and is probably due to experimental scatter. These results show that the temperature will not change the mechanical properties of the alloys during creep experiments or during forming processes, because they do not last for more than 24 hours (mostly under 6 hours). The effect of temperature is stronger at higher temperatures.

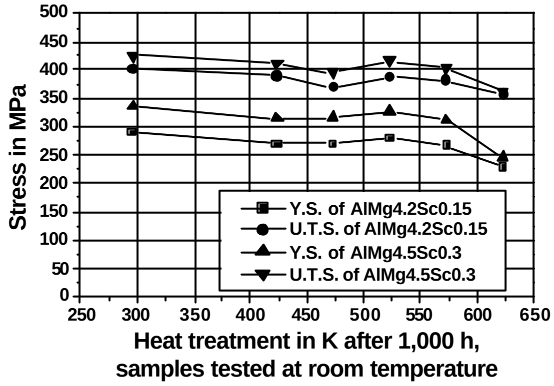

Figure 2: Thermal stability of alloys as a function of heat treatment (X K/1,000 h).
Remark: Alloy AlMg4.3Sc0.15: samples in L-direction, thickness: 4 mm; Alloy AlMg4.5Sc0.3: samples in L-direction, thickness: 1.6 mm

The microstructure of the alloy is very fine and the Al-Mg grains are so flat and long that it is almost impossible to distinguish between them.

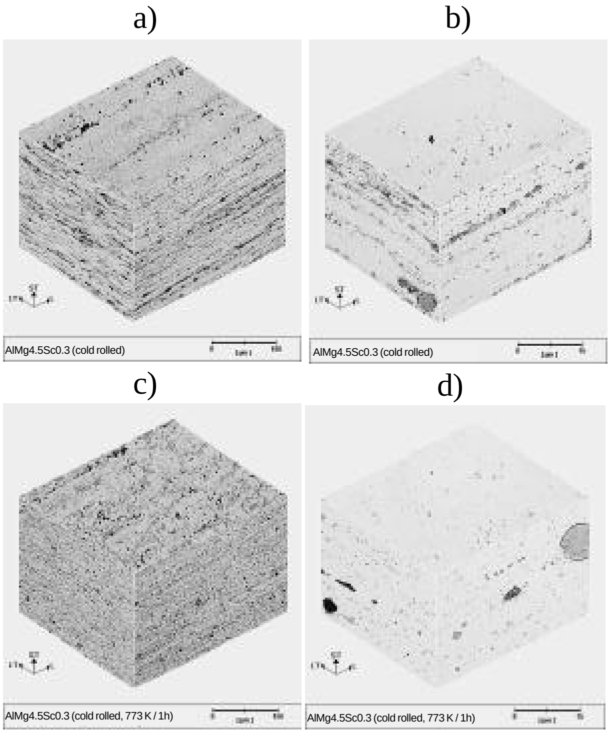

Figure 3: Micrograph of alloy AlMg4.5Sc0.3: a) and b) cold rolled + etched; c) and d) cold rolled, annealed at 773 K / 1h + etched

After 1 hour at 773 K (figure 3-c and 3-d), the microstructure of the alloy AlMg4.5Sc0.3 is similar to the initial one (figure 3-a and 3-d). There are no indications of the commencement of static recrystallization after exposure for one hour at 773 K. This demonstrates that the alloy has good thermal stability. If annealing lasted longer, it is possible that evolution of the microstructure might be observed.

3.1.2 Mechanical properties of AlMgSc alloys at high temperatures

The mechanical properties of the alloys were investigated at high temperatures. The following figure presents the evolution of the mechanical properties as a function of the temperature. No mechanical property was measured above 625 K.

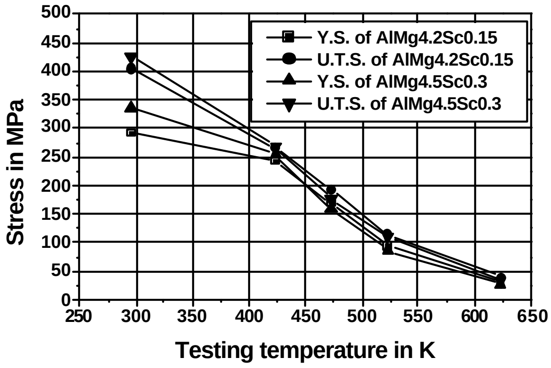

Figure 4: Evolution of mechanical properties as a function of temperature

The mechanical properties of the AlMgSc alloys decrease rapidly above 420 K. The decrease in mechanical properties is greatest in the temperature range between 450 K and 500 K. In this region, the yield strength and the ultimate tensile strength of the two experimental alloys decreases to such an extent that there is a twofold reduction over the value for these properties at room temperature.

Systematic creep experiments were carried out at different temperatures and with different stresses, with the aim of determining the influence of temperature on the viscoplastic properties of the alloy.
The phenomenological power law [7] has been used to calculate the stress exponent:

$$\dot{e} = A \cdot \left(\frac{s}{G}\right)^{n} \cdot \exp\left(-\frac{\Delta Q}{RT}\right) \qquad (1)$$

$\dot{e}$ is the strain rate in s^{-1}, A is a material constant, σ is the applied stress in MPa, G is the shear modulus in MPa, n is the stress sensitivity exponent, ΔQ is the activation energy for flow in $J.mol^{-1}$, R is the gas constant in $J.K^{-1}.mol^{-1}$, T is the temperature in K.

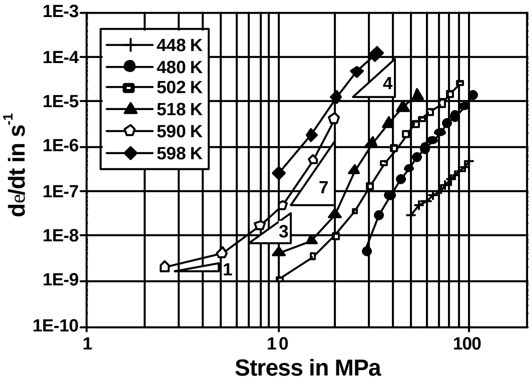

Figure 5: Strain rate of AlMg4.5Sc0.3 (LT), function of normalized stress (tensile load) at different temperatures

As expected, the creep strain rate is significantly dependent on temperature and stress. The stress exponent increases from about 1 to about 3 and further to about 7. It then decreases to around 4 [1]. This behavior was not observed at each temperature because the experiments were not carried out for each stress range. Only two or three creep domains were found for narrower stress regions. The following four creep domains were identified on the basis of temperature range:

- The value of the stress exponent n is about 1 for very low stresses and temperatures around 600 K. A theory has been put forward that the deformation mechanism might be based on a diffusion-mechanism creep (Nabarro-Herring or Coble creep), but this has not been verified.
- The value of the stress exponent n is about 3 for low stresses and this has been associated with the drag of magnesium.
- N is about 7 for intermediate stresses and this has been correlated with the dislocation climb mechanism [11]. A theory has been put forward on the possible influence of scandium precipitates but this has not been verified;
- n is about 4 for high stresses. The scandium precipitates might slow down the dislocation move in this range, similar to a drag mechanism.

The mechanisms occurring differ in part from those observed for Al-Mg solid solutions under similar conditions (amount of Mg, temperature ranges and stress range) [8-10]. The mechanism that occurs with very low stresses is not well understood and more in-depth work on this topic would present an interesting area of research. It would then be possible to form conclusions about the existence of a threshold stress for creep.

Stress relaxation experiments were carried out by changing the temperature in order to determine its influence on stress relaxation in the alloys (figure 6). A threshold stress has been observed depending on different parameters: the direction of rolling, the initial stress and the temperature [1]. From a technological perspective, it is much easier to modify the forming temperature than the other parameters referred to.

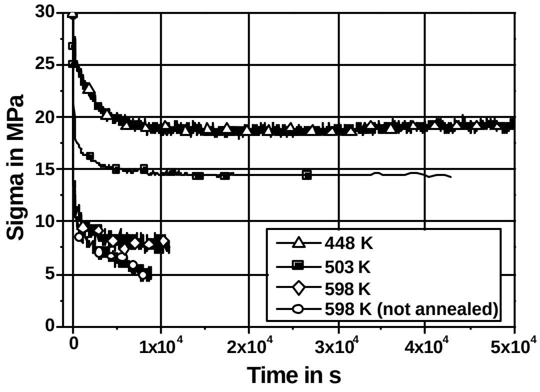

Figure 6: Stress relaxation curves from the AlMg4.5Sc0.3 alloy with an initial stress of 30 MPa at different temperatures (experiments performed with a water-cooled extensometer)

As expected, the speed of material relaxation increases at higher temperatures. When the material is annealed at 598 K, the profile of the stress relaxation curves is similar. The difference between the two curves at 598 K is very interesting, particularly in relation to the technological applications. The profile of the curves is similar at the beginning of the experiments but the stress continues to decrease in the unannealed material. It does not seem to reach any threshold in contrast to the annealed alloy. The contrary was expected: compared to the unannealed sample, the annealed one certainly has a lower dislocation density. This facilitates the local flow responsible for relaxation. Otherwise the load and deformation can facilitate rearrangement of dislocations.

Nevertheless, figure 7 presents a schematic representation of the relationship between the strain rates and the level of threshold stress. From the "industrial point of view", the threshold stress is reached when it corresponds to a strain rate below 10^{-8} s^{-1}.

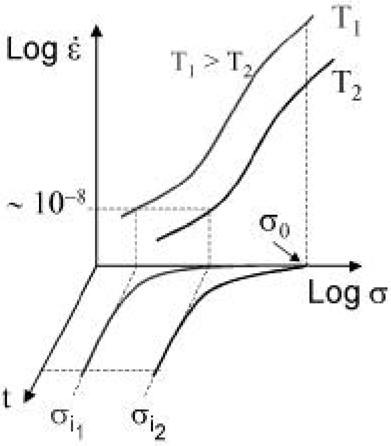

Figure 7: Diagram representing the relationship between the strain rates obtained with creep experiments and the threshold stress from stress relaxation experiments

In reality, the stress continues to decrease very slowly. These findings allow us to conclude that the temperature level plays the main role in determining the apparent threshold stress. The metallurgical properties of AlMgSc alloys offer more possibilities for increasing the temperature of the process because the scandium precipitates preserve the microstructure and mechanical properties of the alloy.

3.2 Application to creep forming

3.2.1 Creep forming at medium temperatures

The material relaxes at medium temperatures, but not enough to obtain the desired contours with the original die (figure 8-b and 8-c). In other words, at 503 K the threshold stress is not low enough and is responsible for spring-back in the shell after the temperature cools and the pressure in the autoclave is reduced. This means that the forming tool must be manufactured with greater curvatures in order to compensate for spring-back in the shell. This process is already well known and is applied to age forming. It requires a computer simulation for the viscoplastic flow of the alloy. The material does not age in the case of AlMgSc alloys. This makes simulation easier because the properties of the material remain the same. The stresses that have not relaxed lead to spring-back in the shell. The new curvatures of the die are tested gradually in order to obtain the right shell contour.

3.2.1 Creep forming at high temperatures

As a result of the high temperatures, the stresses relax to such an extent that after a few minutes they are very low and not strong enough to induce a large spring-back in the shell (figure 8-d, 8-e and 8-f). This is a significant benefit but not the only advantage. The main benefits are summarized as follows.

1. No spring-back (very low) in the shell after forming:
   Computer simulations are not necessary to calculate the appropriate increase in curvature for the forming tool. Furthermore, internal stresses are very low inside the shell after forming.
2. Simplicity of joining the stringers to the sheet by LBW:

The stringers are first welded under plane conditions. This means that the work fixtures are very simple and laser displacement is unidirectional (1D instead of 2D for double-curved components). Secondly, heat treatment at T > 573 K leads to the formation of Al_3Sc precipitates in the welding joint. This improved the mechanical properties. In other words, the filler wire would not be necessary if stringer geometry were adapted. For example, the distances between stringers are smaller, as they are in the rear section of the fuselage. It is easier to weld these parts without any filler wire. Finally the Zeppelin effect (facet formation) due to the use of LBW in joining the stringer to the sheet is lower because the forming step is carried out last (after welding).

3. Reduction of the manufacturing steps for the fabrication of spherical shells:
   It is possible to reduce the number of manufacturing steps from 22 steps for AA2024 (with the conventional stretching and riveting method) or 18 steps for AA6013 and AA6056 (with stretching and LBW method) to 9 steps with the combination of AlMgSc, LBW and creep forming. Forming and heat treatment of the sheet and the stringers are executed in one step. Furthermore, it is not necessary to cut the shell and the stringers after forming them, because there is no clamp area. These are the two main reasons for the low number of manufacturing steps.

4. Minimization of material waste:
   Milling of the shell is carried out before forming (plane conditions) and it could be possible for this to be executed mechanically. This means that the chips can be easily collected and remelted. As indicated in the previous point, it is not necessary to cut the shell and stringers after forming because there is no clamp area and there has been no deterioration (unlike with stretch forming or forming by bending). A few square meters of sheet are saved for each shell

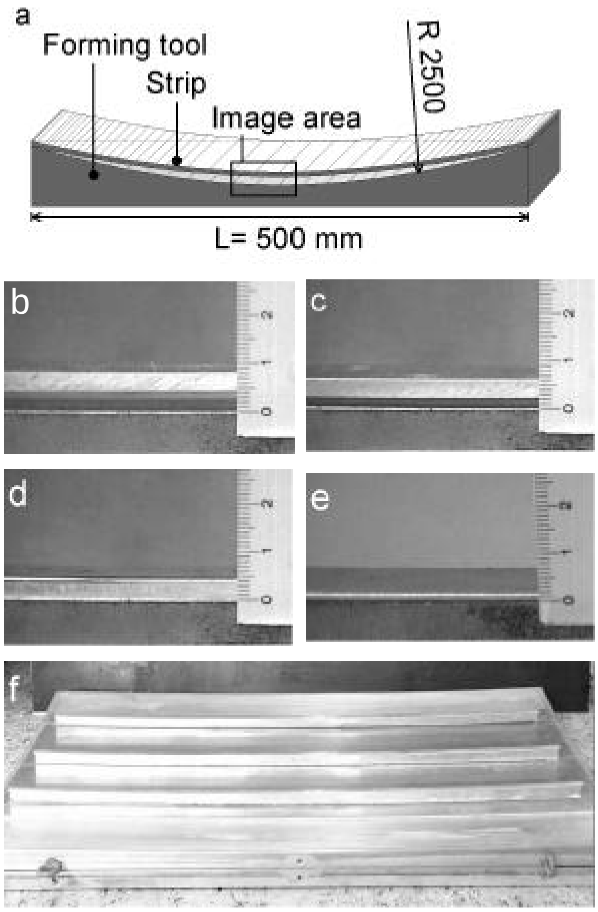

Figure 8: Creep forming in small strips (thickness of b, c, d = 4 mm, e = 1.6 mm) using a cylindrical forming tool (a) at 448 K (b), 503 K (c) and 598 K (d, e, f). f): Part of a creep formed fuselage shell at 598 K (500 x 1000 x 4 mm, length radius: 12 m, crosswise radius: 2.5 m) with three LBW stringers. No spring-back is visible

Conclusion

The most interesting technological application of the study concerns the manufacture of fuselage parts with AlMg4.5Sc0.3 alloy at 598 K by applying the creep-forming process. Other hot forming processes might be considered such as hot-stretch forming but these have not been studied in this paper. The principal advantages of the creep-forming process with AlMgSc alloys are:

- Possibility of forming the alloy without spring-back at the end of the process.
- Conservation (or increase: weldment joint) of the mechanical properties of the alloy after forming at elevated temperatures. The part played by the scandium precipitates made this possible.
- Simplicity of using LBW to join the stringers to the sheet under planar conditions, with or without filler wire (with an adapted stringer geometry).
- Very important reduction of the manufacturing steps needed for a fuselage shell. Of 22 steps needed using conventional riveting of AA2024, only 9 are necessary in order to make a similar part.

Fabrication of fuselage shells with this method might still be slightly improved by reducing the process duration. Such modifications are not always simple to perform without changing the alloy properties. Nevertheless, reduction of the process duration may be envisaged without alloy properties deteriorating.

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