Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2004-266

Influence of heat treatments and straining steps on mechanical properties in the stretch forming process

E.N. Straatsma* and L. Velterop

* Stork Fokker AESP

This report has been based on a paper presented at 9th International Conference on Aluminium Alloys, at Brisbane on August 2-5, 2004.

Customer:	National Aerospace Laboratory NLR
Working Plan number:	S.1.A.1
Owner:	National Aerospace Laboratory NLR
Division:	Aerospace Vehicles
Distribution:	Unlimited
Classification title:	Unclassified
	July 2004

Approved by author:	Approved by project manager:	Approved by project managing department:
20/7	20/7	20/7 '04

Summary

In the aerospace industry, stretch forming of heat-treatable aluminium sheet is a widely used forming method. Simulation of the stretch forming process with FEM is helpful to predict the strain distribution in complex products, to find out the limits of the forming process, and to optimize the amount of strain in each step. Therefore, tensile tests are carried out to determine the influence of intermediate annealing in combination with straining steps on the mechanical properties of AA2024 T3. Since multiple stretching steps with intermediate annealing can influence the grain size and cause visible defects, the development of the grain size in AA2024 T3 is also studied.

Contents

(10 pages in total)

Influence of heat treatments and straining steps on mechanical properties in the stretch forming process

E.N. Straatsma[1] and L. Velterop[2]
[1] Stork Fokker AESP, Industrieweg 4, 3351 LB, Papendrecht, NL
[2] National Aerospace Laboratory NLR, Voorsterweg 31, 8316 PR Marknesse, NL

Keywords: AA2024, Mechanical properties, heat treatment, strain steps, process simulation, stretch forming.

Abstract

In the aerospace industry, stretch forming of heat-treatable aluminium sheet is a widely used forming method. Simulation of the stretch forming process with FEM is helpful to predict the strain distribution in complex products, to find out the limits of the forming process, and to optimize the amount of strain in each step. Therefore, tensile tests are carried out to determine the influence of intermediate annealing in combination with straining steps on the mechanical properties of AA2024 T3. Since multiple stretching steps with intermediate annealing can influence the grain size and cause visible defects, the development of the grain size in AA2024 T3 is also studied.

1. Introduction

Stretch forming of heat-treatable aluminium sheet is widely used in the aerospace industry for production of open shapes like leading edges and engine cowlings. For complicated shapes, with doubly curved surfaces, the final shape is reached only after several forming steps with intermediate annealing treatments, because of strain hardening in the sheet. Traditionally, the forming steps and die shape are defined using production experience and are improved by trial and error. This is a costly and time-consuming way that may lead to sub-optimal solutions.

As stretch-forming machines are operated with displacement control, knowledge of the material properties in the forming condition is not required for the process itself. For simulation of the stretch-forming process with for instance FEM, the mechanical properties of the material must be known in the forming condition. Such simulations can be used to predict the strain distribution in the sheet for each step. This way, the stretch-forming steps can be optimized. Also, the die shape can be varied easily in the simulations, which again reduces the costs to come to an efficient stretch-forming process.

The stretch forming process applied for complex geometries consists of several stretching steps with intermediate annealing treatments at 340 ºC. The annealing treatments remove the strain hardening of the previous step [1], [2]. The material properties of AA2024, which is the focus of the present paper, are well known for several conditions, amongst others the high strength conditions (T3, T4, T8 and their derivatives), but also the full-annealed condition (O) [3]. However, the properties after intermediate annealing for AA2024 are unknown. Only a schematic graph of the influence of several ageing and overageing conditions is given in reference [3] for AA2036. This graph shows that the strength decreases due to overageing while the strain to fracture only increases upon strong overageing. Further, the stretched material has to be solution heat treated to obtain the required mechanical properties. Solution heat treatment causes recrystallization after a critical amount of strain, which results in orange peel [4]. This phenomenon is unacceptable in case of polished skin products. However, the influences of strain steps and intermediate anneals on the developing of orange peel are also unknown.

The present paper focuses on the material properties of AA2024 T3 after several stretching steps and intermediate annealing treatments. The results provide data for simulations.

2. Experimental

Both tensile testing and grain size measurements were applied to study commercial AA2024 Clad in T3 temper with a thickness of 1.6 mm. From two batches of material, A and B, tensile test specimens were made in accordance with ASTM E8 for thin sheet (see figure 1). Each sample was first annealed at a temperature of 340 °C for 30 minutes, which is a common treatment to relieve stress [1],[2]. After this treatment the samples were given several strain steps with each strain step followed by an intermediate heat treatment. The strain was applied in one or two steps (2, 4, 6, and 2x2.5%) for batch A and in steps of 8% with a total strain of 24% for batch B. In total, about 200 tensile tests are carried out. Both batches were tested in the rolling direction and batch A was also tested in the transverse direction and in the direction 45° to the rolling direction. The specimens were tested in a tensile machine with a velocity of the cross-head of 3 mm/min. The strain is measured from the local length of the specimen. From the tensile tests the yield strength, the ultimate tensile strength and the strain to fracture were measured in the annealed temper and in the T42 temper. The solution heat treatment was performed at 495 °C for 30 minutes followed by quenching in water. Optical microscopy was used to determine the grain size according to the linear intercept method from ASTM 112-96.

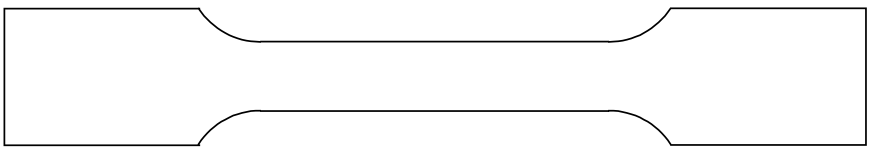

Figure 1. Sample used for tensile experiments. Gauge length either 120 mm (batch A) or 60 mm (batch B).

3. Results

Figures 1a and 1c show the ultimate tensile strength of AA2024 T3 material. It is seen that the tensile strength of T3 material drops enormously for both material batches after the first annealing treatment at zero strain. The tensile strength decreases from 440 MPa to 290 MPa. Increasing the strain with large strain steps, as well as with small strain steps, causes a small additional decrease in tensile strength. Further, it is seen that the values of the tensile strength of batch A are similar to the values of batch B. This is also true for the tensile strength in the other two directions of batch A.

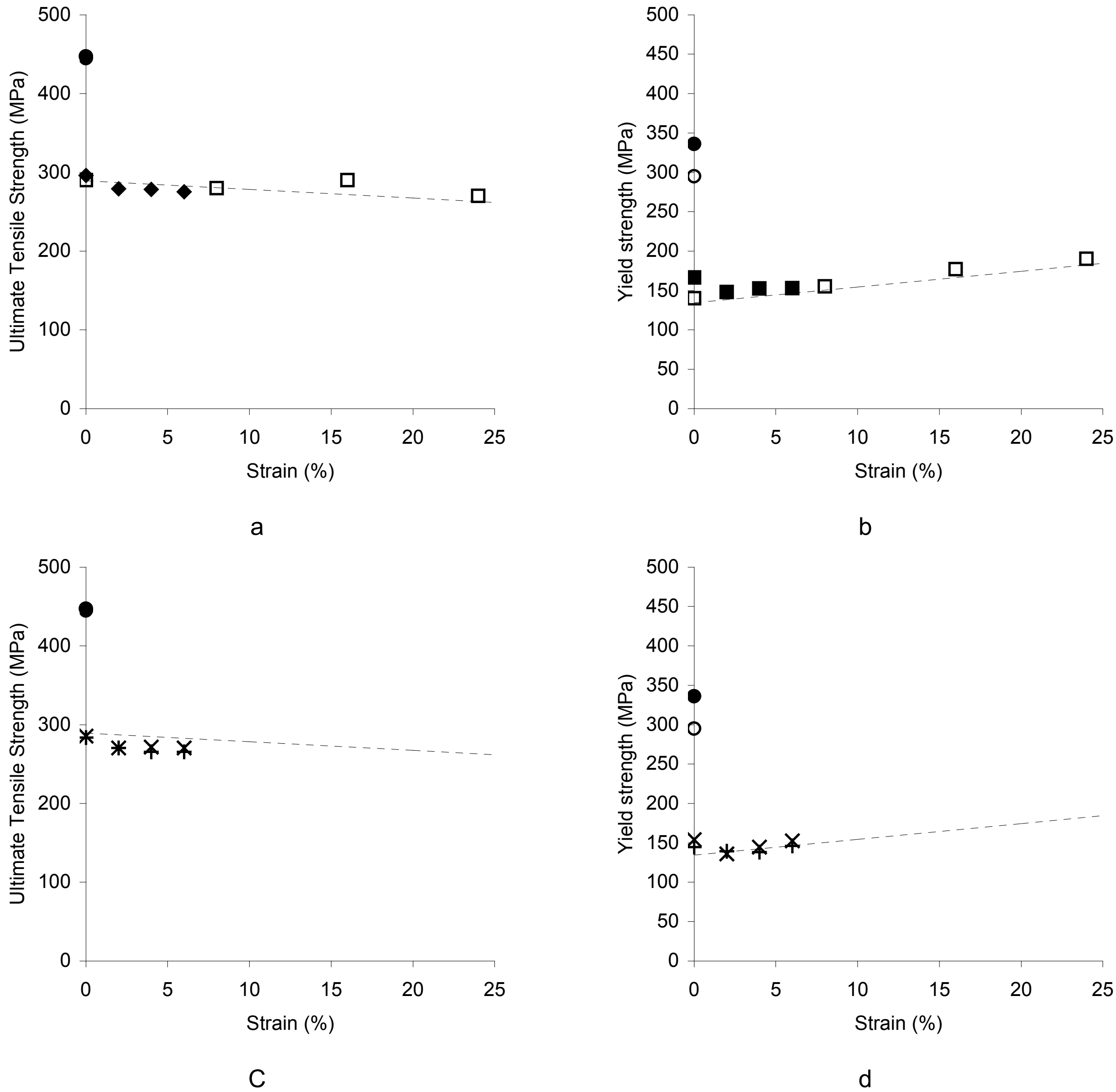

Figure 2. Tensile strength (a, c) and yield strength (b, d) of AA2024 T3 material (●,○) and after intermediate annealing as a function of strain. Tensile strength (◇,◆); Yield strength (■,□). *Material of batch A (solid) and batch B (open). Transverse direction (✚) and 45º to the rolling direction (✖).*

Figures 2b and 2d show the yield strength of AA2024 T3 material. It is seen that, just like the tensile strength, the yield strength also drops enormously after the first annealing treatment at zero strain. The yield strength of batch A and batch B decreases to170 MPa and 140 MPa respectively. Increasing the strain with large strain steps, or small strain steps, causes a slight increase of the yield strength. Further it is seen that the values of the yield strength of batch A are similar to those of batch B and that the values of batch A in the other two directions do not differ much from those for the rolling direction.

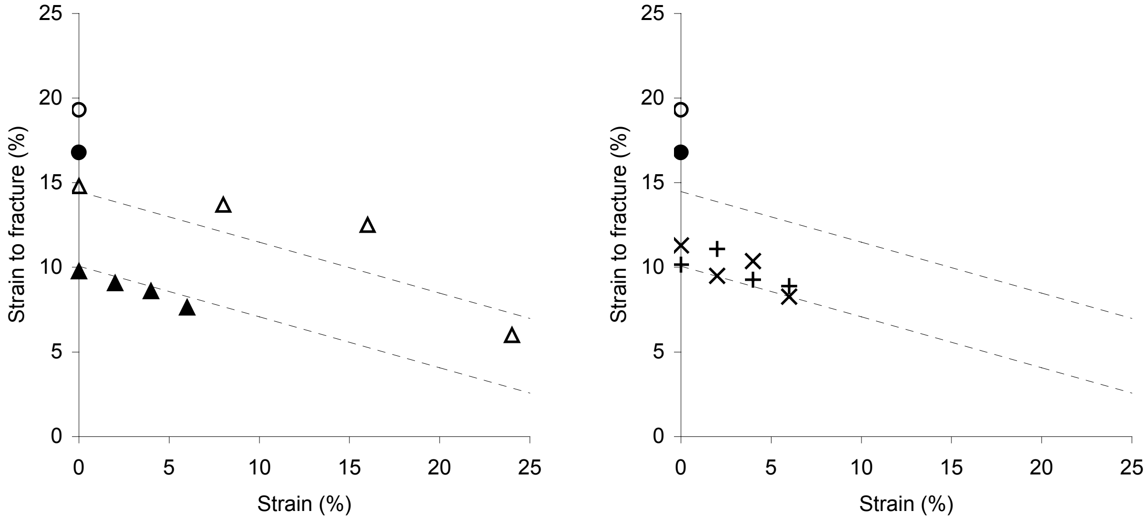

Figure 3. Strain to fracture of AA2024 T3 material (●,○) and after intermediate annealing as a function of strain (▲,△). Material of batch A (solid) and batch B (open). Transverse direction (✚) and 45º to the rolling direction (✖).

Figure 3 shows the strain to fracture of AA2024 T3 material. It is seen that the strain to fracture drops for both batches of material after the first annealing treatment at zero strain. The strain to fracture of material of batch A and batch B decreases to 10% and 14% respectively. For both batches of material increasing the strain, with either large or small strain steps, causes a significant decrease of the strain to fracture. However, the magnitude of the decrease differs for the two batches. Material of batch A shows smaller values for the strain to fracture than material of batch B. Also, the values for batch A in the rolling direction are smaller than the other two directions.

Figure 4 shows the mechanical properties in the T42 temper. It is seen for material of batch B that all properties decrease with increasing strain. The properties from material of batch A correspond well with those of batch B.

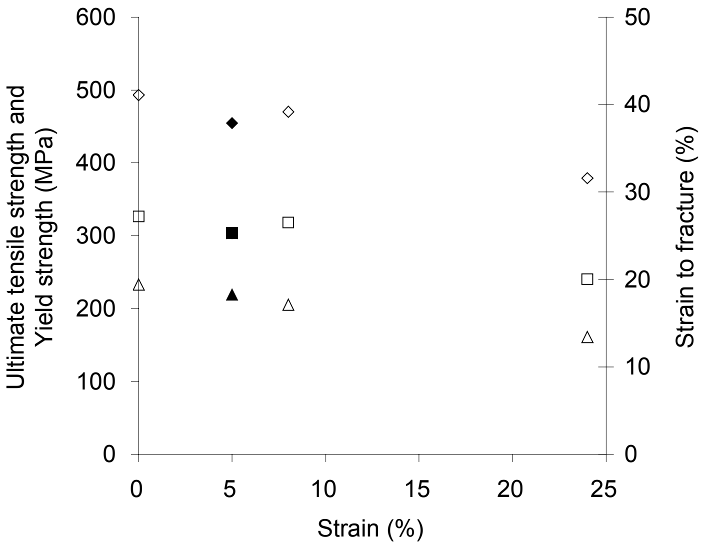

Figure 4. Mechanical properties of AA2024 in the T42 temper as a function of strain. Tensile strength (◇,◆), yield strength (■,□), strain to fracture (▲,△). Material of batch A (solid) and batch B (open).

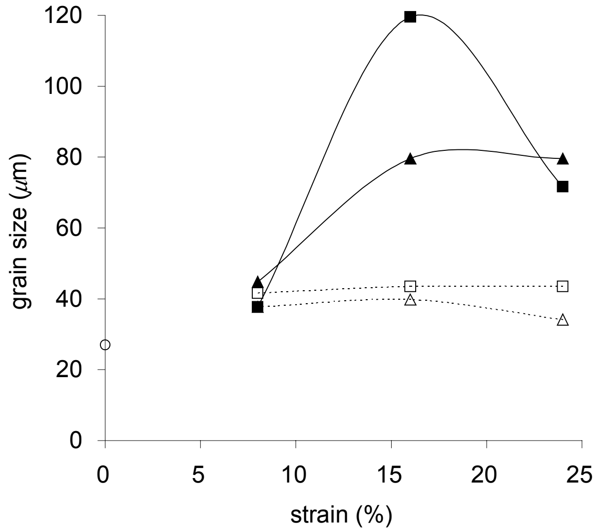

Figure 5. Grain size before the solution heat treatment (open) and in the T42 temper (solid) as a function of strain. Rolling direction (▲,△) and transverse direction.(■,□).

Figure 5 shows the grain size as a function of total strain. It is seen that the grain size is more or less constant in both directions before the solution heat treatment. After the solution heat treatment, in the T42 temper, the grain size increases for total strains between 8% and 24%. The grain size in the rolling direction is much larger at 16% strain than in the transverse direction. Further for the samples with a total strain of 16% it was observed that the surface becomes rough during tensile testing in the T42 temper, which is a well-known phenomenon called orange peel. However, in practice the orange peel is much coarser.

4. Discussion

When the changes in tensile strength and yield strength are compared as a function of strain and annealing, it is seen that both strengths show a large decrease after the first annealing treatment at zero strain. The decreased strength after the first annealing treatment is expected and is a result of overageing (coarsening of precipitates) during the annealing treatment [1],[3]. Further it is seen that with increasing strain the tensile strength (UTS) decreases while the yield strength (YS) increases. The trend to lower UTS with increasing strain steps correlates very well with the lower strain to fracture shown by these specimens because a lower strain to fracture naturally produces a lower UTS provided that work hardening rates are unchanged. However, for the current reduction in strain to fracture, the increased YS should have provided a higher UTS. This effect is eliminated because the work hardening rates decrease with increasing strain. This means that the strain hardening in the consecutive annealing treatment is totally relieved in case of UTS and only partly relieved in case of YS. Apparently, the YS is less responsive to full recovery than the UTS. Since the trends for the tensile strength and yield strength are similar for both batches of material in the annealed condition, the following quantitative equations can be formed:

$$UTS_{\text{annealed}} = -1.1\varepsilon + 0.6UTS_{\text{T3}} \quad (1)$$

$$YS_{\text{annealed}} = 2.0\varepsilon + 0.4YS_{\text{T3}} \quad (2)$$

with ε is the total strain, and UTS_{T3} and YS_{T3} are the ultimate tensile strength and yield strength in the T3 temper respectively.

The strain to fracture is found to decrease with increasing strain, which is also caused by overageing due to annealing treatments. However, the two batches show a large difference in magnitude that are probably caused by differences in the hot rolling process. In practice, unexpected failure sometimes occurs in stretch forming which is ascribed to these differences in strain to fracture after annealing. Both batches show, with consecutive strain steps, a similar decrease in the strain to fracture, but the lowest value is of importance to determine limits of stretch forming. Therefore, the following (conservative) equation can be formed for the strain to fracture in the annealed condition ($\varepsilon_{\textit{fracture annealed}}$):

$$\varepsilon_{\text{fracture annealed}} = -0.3\varepsilon + 0.6\varepsilon_{\text{fracture T3}} \quad (3)$$

with $\varepsilon_{\textit{fracture T3}}$ is the strain to fracture in the T3 temper.

It appears that the tensile strength, yield strength and strain to fracture in the T42 temper start at a higher value than the initial value in the T3 temper. After consecutive strain steps and annealing, all mechanical properties in the T42 temper decrease as a result of the intermediate annealing that is given before the solution heat treatment. After 8% total strain the values become lower than in the T3 temper. Normally the properties in the T4(2) temper are lower than in the T3 temper, which is advantageous in stretch forming because of less spring back. However, the results of this study show that stretch forming in the T42 temper can result in more spring back due to an increased yield strength.

Surface roughening (orange peel) in practice is much coarser than observed in the test specimens. There are two possible explanations for the coarser orange peel. One explanation is that it is caused by a scaling effect. The total strain in local areas determines whether recrystallization will occur [1] and from Figure 5 it is seen that this happens between 8% and 24% total strain, which is confirmed by [1],[4]. In a large sheet, areas with different strain states occur due to geometry differences. Therefore, recrystallization starts separately and grain growth is not hindered. In the test specimens, the total strain is equal in all parts. Hence recrystallization starts in the whole sample, which will limit the grain growth. This limited grain growth can result in smaller scale orange peel after stretching. The second explanation is that it is caused by differences in texture. Since areas with large strains develop stronger deformation textures it is possible that these areas, where most crystals are oriented similarly, behave as large grains and produce coarse orange peel.

5. Conclusions

To be able to simulate the stretch forming process with AA2024 T3 material the mechanical properties of annealed (and strained) material are determined. It is concluded that:

1. a first annealing treatment of T3 cause a large decrease of the mechanical properties.
2. the size of the strain steps does not influence the mechanical properties, only the total strain is important.
3. consecutive strain steps and intermediate anneals slightly decrease the tensile strength and increase the yield strength. There is no influence of the material batch.
4. consecutive strain steps and intermediate anneals decrease the strain to fracture significantly. The batch of material has a large influence on the strain to fracture in the annealed condition.
5. the final properties in the T42 temper are higher than in the initial T3 temper for less than a total strain of 8%.

References

[1] Metals Handbook, 10th edition Vol. 4: Heat Treating, edited by J.R. Davis, G.M. Davidson, S.R. Lampman and T.B. Zorc, ASM International, Materials Park, Ohio, 1997, 841-879

[2] H.Y. Hunsicker, Aluminum, Vol I: properties, physical metallurgy and phase diagrams, edited by K.R. van Horn, American Society for Metals, Metals Park, Ohio, 109-162, 1967

[3] J.W. Bray, Metals Handbook, 10th edition Vol. 2: Properties and Selection: Nonferrous Alloys and Special Purpose Materials, edited by J.R. Davis, P. Allen, S.R. Lampman and T.B. Zorc, ASM International, Materials Park, Ohio, 1990, 29-61, 70-72

[4] D. Althenpohl, Light Metal Age, December 1982, 12-19.