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Enhancement Of Forming Limits Of Aluminum Alloys Using An Intermediate Heat Treatment

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Abstract: Since the lightweight material aluminum exhibits reduced formability compared to conventional steel grades, additional steps for extending the existing forming limits have to be conducted. This paper presents an innovative approach for heat treatment embedded between two cold forming steps. The application of such intermediate heat treatment may reduce the strain hardening of the material which was induced during a first cold forming step. The alloy discussed in detail is AlMg4.5Mn (AA5182). The heat treatment, e.g. in a furnace, should take place at a predefined temperature for a certain duration. This allows a higher degree of deformation in the second forming operation. The advantages of this methodology can be shown by conducting tensile tests. Tensile specimens are first pre-strained to a defined strain value and then heat treated in a way that the recrystallization of the aluminum alloy is avoided. After cooling down the samples to room temperature, further tests are conducted up to failure of the material. As a result of the experiments, stress-strain curves dependent on the heat treatment condition are obtained. Comparing the different curves the support of the heat treatment on formability can be analyzed.

Keywords: aluminum alloy, sheet metal forming, heat treatment.

PACS: 81.05.Bx, 81.40.-z, 81.40.Ef, 81.40.Gh, 81.70.Bt, 62.20.M.

INTRODUCTION

The actual intense debate concerning the reduction of environmentally harmful CO₂ emissions causes at present a trend reversal in the automobile industry. Over the past few years, a range of factors that includes increasing safety requirements and standards of comfort has led to a steady increase in vehicle weight [1]. In order to counter this negative trend, it is essential to intensify and expand the use of lightweight construction in modern vehicles. As a result, the topic of lightweight design and the associated selection of materials are shifting increasingly to the forefront of development activities of the automobile manufacturers [2].

In the body in white an appreciable growth particularly in the use of lightweight materials such as aluminum alloys can be noticed. Aluminum combines many positive characteristics, above all, a low density, an excellent corrosion resistance, a comparatively good formability and a high level of recyclability.

For applications in automobile construction primarily alloys of the naturally hardened AA5xxx-series and the precipitation hardened AA6xxx-series are used. Due to the typical formation of visible and therefore undesirable surface defects [3], so called stretcher strain marks, the use of the AA5xxx alloys is confined to structural components. Such inner panels are not subject to particular surface quality requirements.

The limited formability of aluminum alloys in comparison to steel sheet at room temperature necessitates the extension of existing material constraints. The use of thermal energy opens up significant possibilities for improved deep drawing capabilities [4, 5]. Scientific investigations primarily focus on the heat treatment of materials prior to or during a metal forming process. For this purpose, the yield point is reduced. The Tailored Heat Treated Blanks (THTB) process is characterized by the use of selective local heat treatment of AA6xxx alloys prior to the cold forming process. By applying an adapted thermal layout in order to dissolve the Mg_2Si clusters, it is possible to reduce the yield strength locally and, in doing so, to optimize the material flow [4]. Using inductive heating it is also possible to soften the material locally [5].

In contrast to THTB, the significant feature of warm forming processes are increasing elongation values with rising process temperatures while the strength is reduced [6, 7]. The disadvantages of such warm forming processes are mainly the process time and costs. Another important point is the demand at the current available standard lubricants. These are mostly difficult to remove and unusable for high temperature using.

The principle of an “intermediate heat treatment” (IHT), presented in this paper, combines an innovative solution for improving the formability of conventional aluminum alloys with advantages in process strategies [8]. The application of heat treatment between two cold forming steps allows greater utilization of the material’s ductility. Ultimately, unequivocal results from tensile tests carried out on the AA5182-O alloy verify that elongation values increase as the yield strength simultaneously declines.

PRINCIPLE OF INTERMEDIATE HEAT TREATMENT

Prior investigations have shown that an induced strain hardening in a material can be reduced by the application of an appropriate heat treatment [9, 10, 11]. The IHT method takes advantage of this effect and can be applied as an additional process during the cold forming of aluminum sheets. The investigations carried out as part of this work are focused on the aluminum alloy AA5182-O (AlMg4,5Mn). The aluminum blanks used for this purpose do not require any separate pretreatment by the suppliers, such as special temperature control in the rolling mill or the provision of a surface coating.

The aluminum blank is pre-strained during an initial cold forming step at room temperature, (Fig. 1. (a)), only up to a specific forming degree, typically 10 till 15 %. The reason is to induce selective strain hardening as a consequence of an increase of the dislocation density in the crystal lattice [10]. This is associated with an increase of the yield strength accompanied by a reduction of elongation.

FIGURE 1. (a) Illustration of the intermediate heat treatment process and (b) the theoretic scheme with the effect on the stress-strain curve.

The second subsequent process step involves subjecting the preformed component to selective heat treatment. The temperature-time-window required to achieve the desired reduction in strain hardening is determined.

Figure 1 (b) clearly illustrates the theoretical background of the heat treatment effect on the stress-strain curves. As a result of the heat treatment, accumulated dislocations in the strain hardened material are deleted [9]. At this point, a general distinction is made between recovery and recrystallization processes [10].

If heat treatment is conducted below the recrystallization temperature, lattice imperfections are annealed and rearranged, which causes the microstructure to recover [9]. Consequently, the yield strength declines virtually to its initial level. As a result of this effect, the material is recovered and can reach higher elongation values while retaining the strength required for the next process step. There is no impact with heat treatment on sheet thickness by thinning. The heat treating above the recrystallization temperature reforms the microstructure. Hence the material is fully softened and its ductility increases [9].

The heat treatment as applied in this paper can be carried out in a standard furnace. During the last cold forming step, the relevant semi-finished part is deep drawn into its final geometry. The process makes it possible to produce geometries that cannot be achieved solely by means of cold forming without intermediate heat treatment.

Material and Experimental Procedure

The experimental verification of the increase in elongation achieved by the use of IHT process was obtained using tensile tests carried out in accordance to DIN EN 10002, taking into account the testing standard PuD for aluminum. PuD specifies testing procedures and the final data processing for aluminum alloys [12]. All results relate to a non-heat treatable alloy of the type AA5182-O (AlMg4.5Mn) with a sheet thickness of 1.5 mm. The yield strength $YS = 142$ MPa and a uniform elongation of $UE = 24\%$ were determined in the initial state. The specimen were taken vertically to the rolling direction and exhibited a standardized measurement length of 80 mm.

In order to represent the first cold forming step, all specimens were initially selectively strain hardened. In contrast to the heat treatable 6xxx-alloys, the AA5182-O is a non-heat treatable alloy. In order to determine the relationship between this property

and pre-straining, the test specimen were pre-strained to an average forming degree of 5 % and a higher forming degree of 15 %, without causing a percentage reduction of area.

After pre-straining the tensile specimen were heat treated in a laboratory furnace. The temperature of the test pieces during this process was varied between 200 °C and 450 °C. As a result, it is possible to show an explicit dependency of mechanical properties on temperature and pre-straining. Three thermocouples (type K) were fixed inside a dummy test piece to ensure a precise temperature control. The heating times of the specimens have been chosen to circa 130 s for 250 °C, 200 s for 350 °C and finally 270 s for 450 °C. The differences in the sampling temperature were approximately ± 3 °C. These three selected target temperatures are typical for recovery (250 °C), the recrystallization process (450 °C) and the range between both heat treatment methods (350 °C). First, the focus was heating up the test pieces for reaching the target temperature. After evaluating the test series a second one was started. At this analysis the temperature was maintained for three minutes of target temperature. These investigations of an influence of additional holding time are supposed to determine the mechanical properties dependent on temperature and time. After the heat treatment, the test pieces were removed from the furnace and cooled down at air to room temperature. After this the tensile tests were carried out.

Metallographic analysis is carried out in order to analyze the changes in the grain structure. For this purpose, the microsections were etched by using the Barker-method and investigated in a light microscope.

RESULTS AND DISCUSSION

Figure 2 shows the test results for yield strength and uniform elongation of pre-strained specimen plotted against the maximum temperature. A significant influence of the temperature is clearly recognizable [13]. With increasing temperature, the yield strength shows an almost linear decline. This is accompanied by a simultaneous increase in elongation. The maximum softening effect takes place with a pre-strain of 15% (Fig. 2 (b)) at 400 °C. At this point, the uniform elongation has reached a value of 22 %, in comparison to a primarily uniform elongation of 7.5 %.

FIGURE 2. Mechanical properties plotted above temperature depending on different heating cycles for (a) 5 % pre-strain and (b) 15 % pre-strain.

At a temperature between 300 °C and 350 °C, the initial yield strength of approximately 140-135 MPa is reached. An additional holding time of three minutes at the corresponding target temperature has achieved no significant influence on the mechanical properties. The time for heating up may be sufficient for the desired reduction of strain hardening.

Higher levels of recrystallization effects are expected at a temperature range between 400-450 °C. As a result of complete softening, the value of yield strength has reached approximately 100 MPa. This value is below its initial state of 142 MPa. Based on the selected degree of pre-strain and the heat treatment temperature, the following stress-strain curves are derived shown in Fig. 3. Figure 3 (a) shows the measured curves for 5 % pre-strain and Fig. 3 (b) for 15 % pre-strain. To provide a better comparison, the stress-strain curves are shown for the initial condition (25 °C) and also for strain hardening without a heat treatment.

FIGURE 3. Gauged stress-strain curves for (a) 5 % pre-strain and for (b) 15 % pre-strain with subsequent heat treatment by means of heating-up to three different temperatures (250 °C, 350 °C and 450 °C) in a furnace.

The formation of orange peel on the specimen surface was observed with a pre-strain of 5% and a heat treatment at 450°C. Especially low forming degrees are susceptible for coarse grain [9]. It is assumed that a brittle material behavior is caused by coarse grain and lower strength values. Figure 4 verifies this observation, based on micrographs, showing the tensile tests pre-strained by 5 % heating up to 350 °C (Fig. 4 (a)) compared to those heat treated up to 450 °C (Fig. 4 (b)). It is recognizable that coarse grain has been formed. On this knowledge, the process window is limited, regarding to the maximum heat treatment temperature.

FIGURE 4. Investigated microstructure for 5% pre-strain specimen which has been heat treated at (a) 350 °C and another specimen at (b) 450 °C with visible formation of coarse grain.

CONCLUSION

The application of the IHT process promises a significant increase in the achievable formability of aluminum alloys that have been previously subjected to strain hardening in advance. This was demonstrated by conducting tensile tests using a natural AA5182-O alloy. The optimum temperature range is between 250 °C and 350 °C. The mentioned experiments showed that it is not necessary to hold the target temperature for a specific time after heating up in a furnace. Once the recovery of the material is achieved, it can be used for an additional forming step.

Further investigations will be carried out in order to provide more detailed information of other types of forming conditions.

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