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Comparison of Properties of Extruded 6xxx Alloys in T5 Temper versus T6 Temper

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Abstract

In order to achieve the highest possible potential for age hardening in extruded profiles of 6xxx alloys it is necessary to make sure that as much Mg and Si as possible is in solid solution before the ageing. This can be done either by a separate solution heat treatment, or by making sure that no (Mg,Si) particles are formed in the as-extruded profile prior to artificial ageing. The present paper explains how one can avoid (Mg,Si) particles in the as-extruded profile, and the effect of billet preheating temperature is illustrated by an example from industrial scale experiments. Further, it is shown by examples from semi-industrial scale experiments with 6005 alloys that when precautions are taken to avoid (Mg,Si) particles in the as-extruded profile the T5 strength is at least as good as the T6 strength. In some cases a separate solution heat treatment may actually lead to a much lower strength in the T6 condition.

1. Introduction

Footnote 9 in the AA temper designation system for aluminium alloys [1] allows the T6 designation for extruded profiles in 6xxx alloys that are age hardened to the maximum hardness without a separate solution heat treatment, provided that the achieved strength is similar to that of profiles which are solution heat treated and subsequently aged to the maximum hardness. The intention of this paper is to outline some of the underlying conditions for the achieved strength in the age hardened profile, and to show by industrial and semi-industrial scale experiments how to achieve T6 strength in an extruded profile of 6xxx alloy without a separate solution heat treatment.

One of the key conditions for obtaining the highest possible strength when age hardening an alloy is that as much as possible of the strengthening elements is in solid solution prior to the ageing, and thus is available for the formation of strengthening precipitates. In the case of 6xxx alloys, it is Mg and Si that form the strengthening precipitates.

After casting and homogenisation of extrusion ingots some of the Si will be tied up in primary AlFeSi-particles, and this Si can be considered as "lost" in the context of age hardening. Some more Si will normally be tied up along with Mg in (Mg,Si) particles such as the equilibrium Mg_2Si phase and the metastable β' phase. These phases have formed during the cooling from the homogenising temperature, and can dissolve if the material is re-heated. Some of the (Mg,Si) particles may survive the extrusion process, and some more (Mg,Si) particles may form during cooling of the extruded profile. Either of these events will reduce the potential for strengthening in the subsequent age hardening.

The condition of an alloy that is artificially age hardened to its maximum strength directly after the extrusion process, *i.e.* without any separate solution heat treatment, is known as the "T5 temper". A common way to ensure a maximum amount of Mg and Si available for precipitation during the age hardening is to subject the alloy to a solution heat treatment first. As the name implies, the purpose of this heat treatment is to dissolve (Mg,Si) particles. The condition of an alloy that has been solution heat treated and subsequently artificially age hardened to its maximum strength is known as the "T6 temper".

There is, however, another way to optimise the strength of the alloy. If one manages to dissolve all (Mg,Si) particles in the billet prior to or during the extrusion and avoids the formation of new ones when the profile is cooling, a separate solution heat treatment is not necessary in order to achieve the highest possible strength. It will in fact be shown in this report that when precautions are taken to avoid (Mg,Si) particles during the extrusion process, one consistently achieves a T5 strength that is slightly higher than the corresponding T6 strength.

2. Avoiding (Mg,Si) Particles

The temperature that is needed to dissolve all (Mg,Si) particles depends on the alloy composition, and can easily be determined either by studying the phase diagrams or by experiments. When preheating the extrusion billet before extrusion one should choose a temperature that ensures that all (Mg,Si) particles are dissolved in the profile as it leaves the extrusion die. Due to the deformation resistance the material gets warmer as it passes through the die. Thus the lowest necessary preheating temperature can actually be lower than the solvus temperature. How much lower it can be depends on several factors, amongst them alloy composition, reduction ratio and ram speed.

It is also possible to avoid (Mg,Si) particles for billet temperatures much lower than the solvus temperature. This can be done by heating the billet to a temperature above the solvus temperature, keep it there for sufficient time to dissolve all of the (Mg,Si) particle and then apply a controlled quench to rapidly decrease the billet temperature to the desired level below the solvus temperature. This procedure of preheating the extrusion billets is referred to as “overheating” [2], as opposed to “direct heating” when the billets are heated directly to the desired temperature. When overheating is applied the time between the quenching and the extrusion must be short, otherwise the (Mg,Si) particles will re-precipitate in the billet and the whole point of this procedure vanishes.

How the billet preheating influences the final strength of the profile in industrial practices is illustrated in Figure 1, which relates to an industrial trial on a 27MN extrusion press with Ø203mm (8”) extrusion billets of a 6063-alloy containing essentially 0.53 wt.% Mg, 0.41 wt.% Si, 0.18 wt.% Fe and 0.02 wt.% Mn as alloying elements. The figure shows the variation in ultimate tensile strength of age hardened profiles of this alloy when the extrusion billets are preheated by direct heating to different temperatures in the range 415°C – 495°C and when the extrusion billets are overheated and quenched to temperatures in the temperature range 390°C – 465°C.

Consider first the strength of profiles made from directly heated billets. For low billet temperatures the strength is low, and as the billet temperature increases the strength increases up to a certain level. This reflects that preheating to a low temperature allows a certain amount of (Mg,Si) particles to survive the extrusion process, and thus the age hardening potential of the profile is reduced. At billet temperatures above approx. 460°C the strength does not vary much in this case. This means that all (Mg,Si) particles are dissolved in the extruded material as it leaves the die, and apparently the maximum potential for subsequent age hardening of this alloy is achieved.

In the case of overheating, one finds that the ultimate tensile strength is constant for all the investigated billet temperatures, and further that the level of the strength is approx. equal to the maximum level of the profiles made from directly heated billets. This illustrates that when overheating is performed, one may apply billet temperatures considerabely lower than the solvus temperature and still avoid the loss in strength associated with (Mg,Si) particles in the billet.

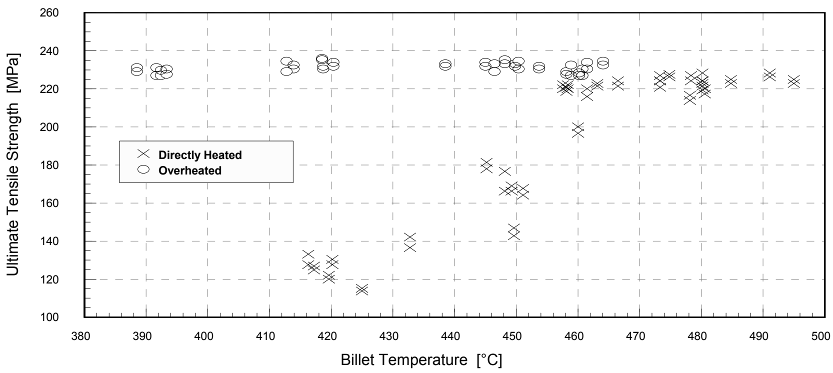

Figure 1: Effect of billet preheating on the T5 strength of extruded sections of a 6063 alloy.

The issue of avoiding (Mg,Si) particle formation as the profile is cooled after extrusion is equally important with respect to retaining Mg and Si in solid solution. There are in general two factors that influence how much (Mg,Si) particles that is formed at a given cooling rate:

1. The Mg and Si content
2. The number of nucleation sites for (Mg,Si) particles.

The formation of (Mg,Si) particles is facilitated when the Mg and Si content is high. Thus, a low alloyed 6xxx alloy might not lose much of the age hardening potential if the profile is air cooled after extrusion while for high alloyed 6xxx alloys a rapid quench is mandatory if one wants to retain the age hardening potential.

(Mg,Si) particles form easily on heterogeneities in the material, such as grain boundaries, dislocations and particle/matrix interfaces. If the material contains significant amounts of Mn or Cr, these elements will form dense distributions of dispersoids during the homogenisation of the extrusion ingot. The dispersoid/matrix interface is frequently found to be a preferred nucleation site for (Mg,Si) particles, and thus a material containing a high number of dispersoids will require a high cooing rate to retain its age hardening potential [3].

The issue of feasibility for strengthening elements to form particles during cooling of extrusions is referred to as "quench sensitivity". If particles form easily during cooling, the material is said to be "quench sensitive"

3. T5 Strength vs T6 Strength

The effect of a separate solution heat treatment on the strength of extruded and age hardened profiles has been recorded for a range of alloys of 6005-type with various levels of Mn and Mn + Cr. The alloy compositions are given in Table 1 below (all in wt.%): The alloys were DC cast as Ø95mm extrusion ingots and homogenised at 575°C for 2h 15 min. Extrusion billets of 200 mm length were cut from the ingots, and extruded to 1.9 mm x 25 mm flat bar profiles at a 800 ton laboratory press at SINTEF in Trondheim.

Table 1: Chemical composition of 6005-alloys measured by an optical emission spectrograph.

	Mg	Si	Fe	Cu	Mn	Cr
Alloy 1	0,54	0,57	0,21	0,14	0,00	0,00
Alloy 2	0,54	0,57	0,21	0,14	0,01	0,00
Alloy 3	0,54	0,57	0,21	0,14	0,03	0,00
Alloy 4	0,53	0,55	0,21	0,14	0,06	0,01
Alloy 5	0,52	0,55	0,21	0,14	0,14	0,01
Alloy 6	0,52	0,56	0,22	0,15	0,15	0,07
Alloy 7	0,52	0,57	0,22	0,15	0,49	0,14

The extrusion billets were overheated, which ensured that all (Mg,Si) particles were dissolved as the profile left the die. Two profiles were made of each alloy, one that was air-cooled after extrusion and another that was water-quenched after extrusion. Material from the as-extruded profiles that was subsequently age hardened to maximum hardness is in the following called "T5 Air Cooled" and "T5 Water Quenched"

Some specimens from the as-extruded water-quenched profiles were given a solution heat treatment in an air circulation furnace. The specimens were kept six minutes in the furnace, ensuring between two and three minutes at a temperature above 530°C, which is sufficient time to dissolve any (Mg,Si) particles formed during heating to this temperature, yet short enough time to avoid measurable grain growth. After this quick soak, the specimens were either air cooled or water quenched. The specimens were subsequently age hardened to maximum hardness and are in the following called "T6 Air Cooled" and "T6 Water Quenched", respectively.

All specimens, both T5 and T6, were aged under the same conditions:

- Stretched 0.4% after cooling
- Kept at room-temperature for 4 hours between cooling and age hardening
- Age hardened at the same temperature cycle

Tensile tests were made of all specimens. The resulting ultimate tensile strength is shown in Figure 2. As one can see, the T5 condition actually gives slightly higher strength than T6 in almost all specimens. The only exception is in the air cooled specimens from alloy 6. The reason for this discrepancy is not known.

The yield strength of the specimens followed the same pattern as the tensile strength.

4. Disadvantages of a Separate Solution Heat Treatment

Besides the increased production cost there are quite a few disadvantages of technological and metallurgical nature in applying a separate solution heat treatment to extruded profiles of 6xxx alloys.

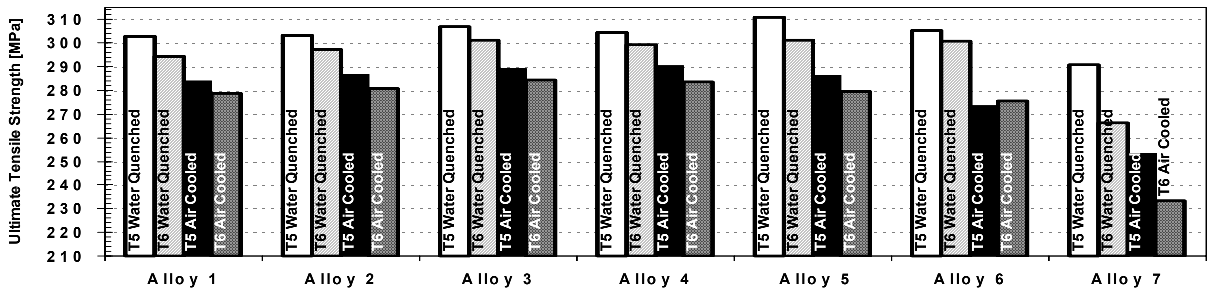

Figure 2: Ultimate tensile strength of extruded profiles of the 6005 alloys of Table 1 after age hardening to maximum hardness as a function of thermal history prior to the age hardening.

In some cases one can lose a considerable amount of strength when applying a separate solution heat treatment prior to the age hardening. These differences are recognised as significant for several 6xxx alloys when comparing T5 and T6 properties in industrial practices [4]. The loss is most prominent when other factors than precipitation hardening contributes significantly to the T5 strength. An example of this is illustrated in Figure 2. All investigated alloys were recrystallised after extrusion, except Alloy 7 with 0.50%Mn + 0.15%Cr. This alloy had a fibrous unrecrystallised structure (except for a thin layer at the surface, which was recrystallised). Thus, some of the deformation substructure (subgrains, dislocations) is still remaining in the as-extruded profile, and gives a significant contribution to the strength of the age hardened material. When solution heat treatment is applied to this profile the substructure recovers, and the strength of the subsequently age hardened material decreases accordingly. This is the reason why the T5 strength is so much higher than the T6 strength for the profiles of this alloy.

In the same manner a separate solution heat treatment can lead to recrystallisation of an unrecrystallised material, or to significant grain growth in a fine-grained recrystallised structure. Any of these events will lead to a lower strength in the T6 condition than in the T5 condition.

The extruded and cooled profiles are straightened by stretching, which introduces a plastic strain of typically less than 1%. Even this small amount of deformation has a significant impact on the age hardening kinetics of 6xxx alloys. Cold deformed 6xxx alloys respond faster to subsequent age hardening than undeformed alloys [5]. If a profile of 6xxx alloy is solution heat treated an is not subjected to subsequent stretching or other cold work such as forming operations prior to age hardening, a longer age hardening time is required to reach the same strength as that of a stretched profile.

Grain growth and abnormal grain growth as a result of solution heat treatment also represents a problem besides the loss of strength. Coarse grains, particularly at the surface, may lead to an uneven surface, often referred to as “orange peel”, during stretching of the profile or during subsequent forming operations. An even grain size at the surface is also important in order to obtain an even and smooth surface finish of anodised profiles. Coarse grains may alter the surface appearance, and abnormal grain growth may result in spots and patches in the surface finish.

Aluminium alloys have very low strength at the temperatures normally applied during solution heat treatment. Consequently there is a risk that the profile may deform at this temperature. This could be due to forces imposed on the profiles during transport in the furnace, or the profile can simply be sagging because of it's own weight.

5. Conclusion

It has been shown that when precautions are taken to avoid (Mg,Si) particles in as-extruded profiles of 6xxx alloys, and thus maximising the age hardening potential of the alloy, the mechanical strength of the profiles in the T5 temper is at least as good as in the T6 temper. In some cases a separate solution heat treatment may actually lead to a much lower strength in the age hardened profile.

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