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INFLUENCE OF SOLUTION HEAT TREATMENT TEMPERATURE IN THE FINAL PROPERTIES OF AA6201 DRAWN WIRE

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Abstract

In order to assess the influence of the solution heat treatment temperature in the mechanical and electrical properties of AA6201 drawn wire, samples were solution heat treated at different temperatures (both above and below the *solvus* limit), quenched, deformed and artificially aged, so as to reproduce the actual wire manufacturing conditions. The relation between the mechanical and electrical properties of the rod and the solution heat treatment temperature was thus obtained, focusing primarily on the practical impact and consequences of such temperature variations regarding the attainable final product properties. It was observed that a minimum solution heat treating temperature of 510°C is desirable in order to reach the optimal conditions for the final product. Failure to reach such temperature leads not only to lower mechanical properties of the wire, but also reduces the elongation to fracture of the rod.

Introduction

AA6201 wires are used in AAAC (All Aluminum Alloy Conductor) overhead power transmission lines. Its benefits compared to conventional ACSR (Aluminum Conductor Steel Reinforced) conductors are lower power losses (the inductive effect of steel is eliminated), excellent corrosion resistance and better resistance to abrasion, all this without compromising neither electrical conductivity nor strength and sag properties [1].

Being one of the 6000 series alloys, its main alloying elements are Mg and Si. Once the rod is manufactured and before being drawn, it undergoes a solution heat treatment and a subsequent quenching in order to dissolve all the Mg and Si and keep it in solid solution. Upon being drawn to the desired diameter, the wire is artificially aged so as to promote a fine precipitation of Mg_2Si, which improves mechanical strength, elongation to fracture, as well as electrical conductivity. Finally, the wires are stranded and the conductor is ready for use in overhead power transmission lines [2, 3, 4, 5].

One of the critical parameters of the overall process of manufacture of AA6201 rod is the solution heat treatment temperature. According to the classical pseudo-binary Al-Mg_2Si phase diagram [6, 7, 8], temperatures ranging from 490°C to 615°C are high enough to dissolve all the Mg and Si into solid solution. However, there exist some publications showing slightly different Al-Mg_2Si phase diagrams [9]. Amado and Daroqui reviewed the phase diagram using electrical conductivity measurements [10]. However, all these reviews and publications focus on a phase-transformation point of view. The aim of this work is to quantify the consequences of solution heat treatment temperature variations in the final product, as well as also in the workability of the rod.

Experimental

Continuously cast and rolled (CCR) AA6201 rod samples were taken directly from the rolling mill. The alloy used has 0.66%wt.Mg, 0.53%wt.Si and 0.20%wt.Fe as the main alloying elements. The samples (370mm long ϕ9.5mm rods) were then solution heat treated in an electrical furnace and quenched in water. The solution heat treatment temperatures ranged from 420°C to 600°C, the samples being soaked at those temperatures for one hour. The samples were natural aged at room temperature for some days, being finally mechanically deformed (some samples were deformed using a tension test machine, while others were drawn using a laboratory drawing machine) and artificially aged. The reason for the mechanical deformation of the samples is to simulate the actual process of the manufacture of wires, which includes a high degree of deformation between the solution heat treatment and the artificial aging. There is also a group of samples that was neither deformed nor artificially aged, in order to assess the properties of the rod from the wire drawer point of view. Mechanical properties as well as electrical conductivity measurements were carried out on the samples. Measurements of the strain hardening exponent were also taken based on the tension tests curves of the samples (Figure 1).

Solution heat treated, deformed and aged samples

Samples were solution heat treated at temperatures ranging from 420°C to 600°C, in steps of 20°C, followed by water quenching. Each group of samples consisted of 20 rods. The soaking time for the heat treatment was 1 hour. After 14 days of natural aging at room temperature, the rods were deformed using a tension test machine: 15% elongation for samples treated at temperatures over 470°C and 7% elongation for samples treated at temperatures lower than 470°C. The reason for the use of different elongations relies upon the fact that the samples treated at 420°C, 440°C and 460°C showed lower elongation to fracture. Finally, the samples were artificially aged at 200°C, with aging times ranging from 0.5 hours to 9 hours (two rod samples for each aging time). Mechanical properties as well as electrical conductivity were finally measured.

Solution heat treated, drawn and aged samples

In this case, samples were solution heat treated at temperatures ranging from 460°C to 540°C, in steps of 20°C, followed by water quenching. The soaking time for the heat treatment was 2 hours. After 28 days of natural aging at room temperature, the rods were drawn from 9.5mm to 3.38mm (75% reduction in area) using a laboratory drawing machine. This reduction was accomplished in 10 drawing steps, each step applying ~20% reduction in area. The drawn wire samples were then artificially aged at 160°C for 3 and 4 hours. Finally, the samples were mechanically and electrically tested.

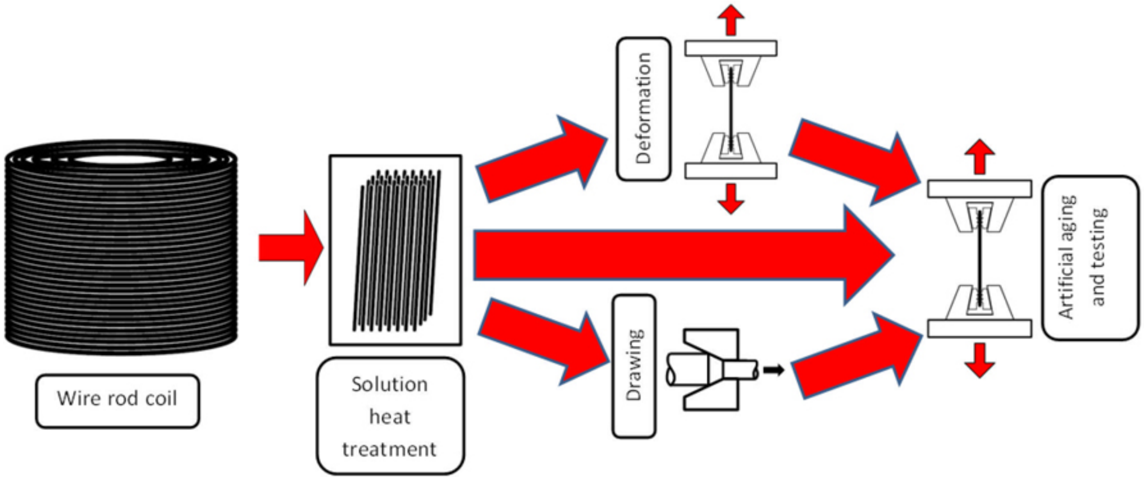

Figure 1. Sampling of rod, heat treatment and mechanical processing schematic.

Solution heat treated samples

This last group of samples was solution heat treated and water quenched at temperatures ranging from 460°C to 570°C, in steps of 10°C. The soaking time for the treatment was 1 hour in every case. The samples were natural aged for 4 days at room temperature and then mechanically tested.

Results and discussion

Solution heat treated, deformed and aged samples

Figures 2(a) and 2(b) show the ultimate tensile strength and the yield strength for the deformed and aged samples. In both figures, the plots could be well divided into three sub groups: the group with highest mechanical strength (for heat treating temperatures above 500°C), a group with a somewhat lower mechanical strength (500°C) and then the last group with significant lower strength (heat treatment temperatures below 500°C). The peak aging condition is reached at around 1 hour aging treatment for the samples deformed 15%, while for the samples deformed 7% it takes around 3 hours. The higher the deformation, the higher the dislocation density and the faster the precipitation of Mg_2Si. Regarding Figure 2(b), at the very beginning of the artificial aging treatment there is a drop in the yield strength. The reason for this softening is that recovery mechanisms are taking place, eliminating some of the previous deformation imparted to the rod. It is therefore seen that the decrease in the yield stregth is higher for the more deformed samples. However, soon thereafter the precipitation of Mg_2Si starts to be more important than the recovery mechanisms, thus increasing the yield strength up to the peak aging condition. Longer treatments lead to an over-aged microstructure, where Mg_2Si agglomerate and coarsen into bigger particles that do not have any strengthening effect.

These markedly different three groups are also noticeable in the electrical conductivity plot (Figure 3). In this case, the most important characteristic is the initial electrical conductivity before and at the beginning of the artificial aging treatment: it is higher for those samples that were treated at temperatures below 500°C. This correlates well with what is expected, then at temperatures below the *solvus* line, some fraction of Mg_2Si remains as precipitates, thus increasing the electrical conductivity of the rod.

Figure 2(c) shows the elongation to fracture of the samples. Here, there is a change in the three above mentioned subgroups. There are two groups of samples, namely those treated at 420°C and 440°C and those treated at higher temperatures. The first group shows a slightly higher elongation to fracture. This could be based upon the fact that these samples were deformed 7% instead of 15%. However, the samples treated at 460°C were also deformed 7% and show an elongation to fracture similar to the rest of the samples. Theoretically, the microstructure of the samples treated below the *solvus* line consists of Mg_2Si precipitates in an α-aluminum matrix. Upon artificial aging, the remaining Mg and Si that is still in solid solution begin to precipitate. Referring to the Mg_2Si particles that remained precipitated during and after the solution heat treatment, they have a size that is too big to produce a strengthening effect on the rods. Moreover, if their size is too big they could be detrimental to the ductility of the material, therefore lowering the elongation to fracture. This may well explain the behaviour of the samples treated at 480°C. These samples have the lowest elongation to fracture of all. According to the classical phase diagram, 480°C lies just below the *solvus* temperature for this alloy, what indicates that there would be some Mg_2Si precipitates during and after the solution heat treatment. Moreover, for the heat treatment temperature is high, the coarsening of these Mg_2Si precipitates is expected to be fast (specifically faster than samples treated at lower temperatures). This has practical consequences regarding the solution heat treament of these alloys, then not reaching the *solvus* temperature has not only a detrimental effect on the maximum attainable mechanical strength, but also a marked drop in the elongation to fracture. This latter aspect is of significant importance to the subsequent drawing process that undergoes the rod.

Solution heat treated and drawn samples

The plots showing mechanical strength, elongation to fracture and

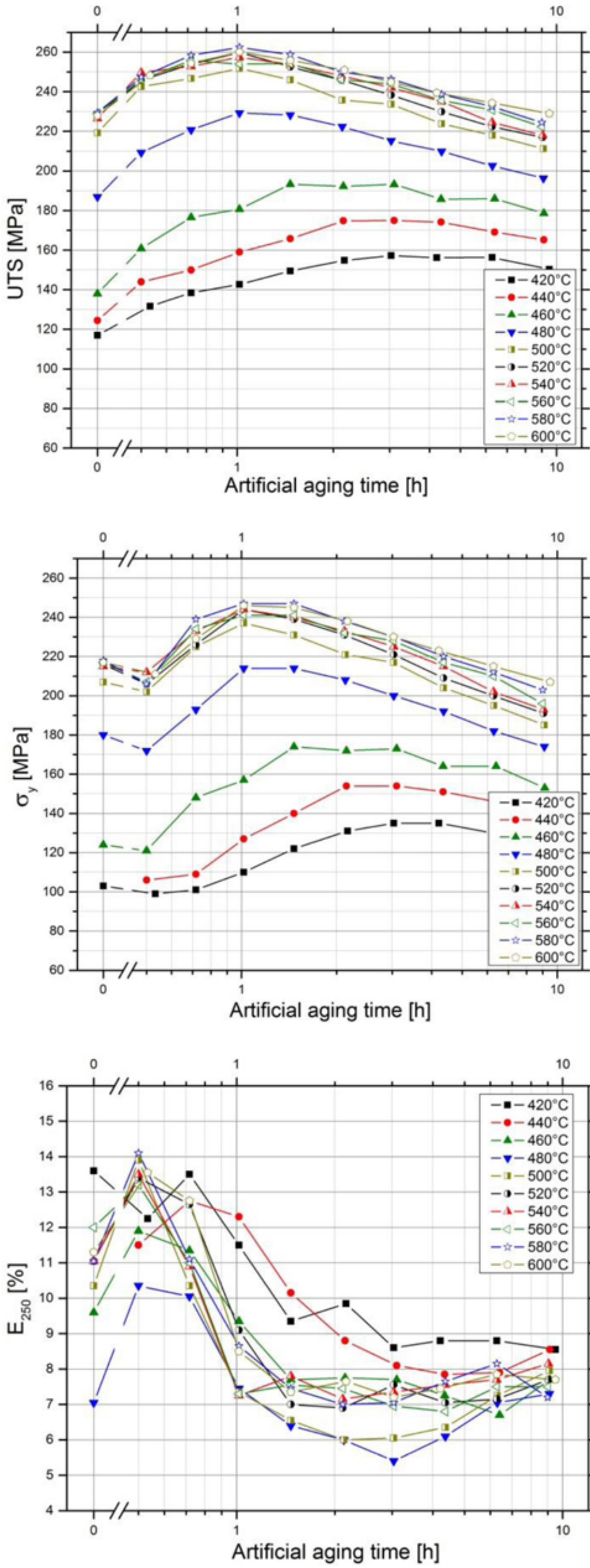

Figure 2. (a) Ultimate tensile strength, (b) yield strength and (c) elongation to fracture against artificial aging time, for different solution heat treatment temperatures.

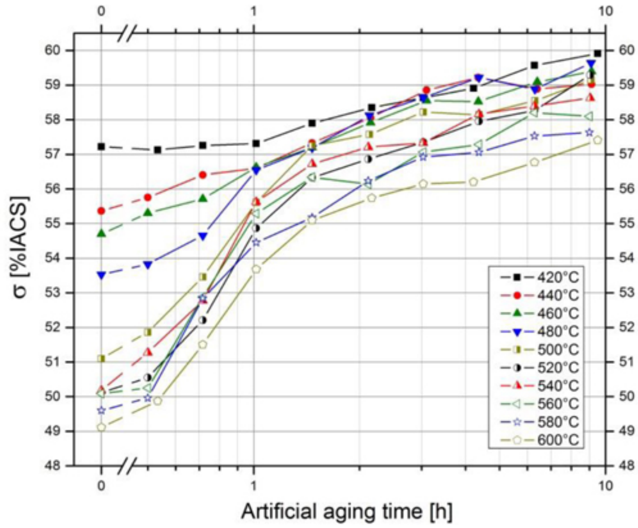

Figure 3. Electrical conductivity against artificial aging time, for different solution heat treatment temperatures.

electrical conductivity of the drawn wire in relation to the solution heat treatment temperature of the rod are shown in Figure 4. In contrast to the deformed samples, in this case the samples were aged at a lower temperature and for 3 and 4 hours. The results show a similar behaviour of the material to that obtained with the deformed samples: solution heat treatment temperatures from 460° to 500°C show a continuous improvement in the mechanical properties of the rod and of the wire. Regarding the mechanical strength of the drawn and aged wire, there is a decrease of around 15% in the UTS of the wire when lowering the solution heat treatment temperature from 520°C to 480°C. The elongation to fracture of the 500°C solution heat treated samples is somewhat lower, but it increases when the heat treatment temperature is increased to 520°C or higher. From Figure 4 it is also clear that in this case the artificial aging does not improve the mechanical strength of the drawn wire. This is due to the high rate of work hardening imparted to the wire during the drawing, which is the main factor contributing to its strength. However, the artificial aging treatment is of critical importance in improving the electrical conductivity as well as restoring the elongation to fracture, this latter aspect being necessary for the subsequent stranding of the conductor. Finally, it is worth mentioning that for all solution heat treatment temperatures equal and over 480°C, the wire obtained in this work meets the ASTM B398 specification for mechanical strength as well as for electrical conductivity [11].

Solution heat treated samples

The plot in Figure 5 shows the mechanical strength, elongation to fracture and the strain hardening exponent of the rod for different solution heat treatment temperatures. Again, the plots show that the minimum heat treatment temperature in order to obtain the optimal conditions upon aging lies around 510°C. This temperature differs from that obtained in some previous works [8, 9]. However, it correlates well with that reported by Amado and Daroqui [10]. Regarding the elongation to fracture, the drop of this parameter around 480°C that was observed in the deformed samples is also seen in these solution heat treated rod samples, with a minimum elongation to fracture at 490°C. It is good to

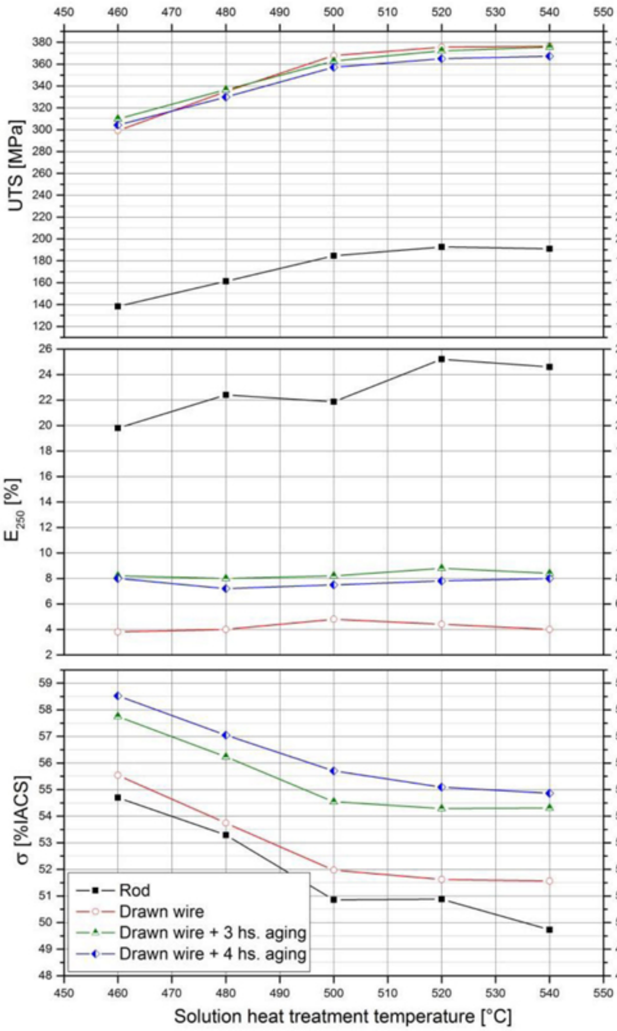

Figure 4. Ultimate tensile strength, elongation to fracture and electrical conductivity of rod and drawn wire (*as-drawn* and artificially aged), for different solution heat treatment temperatures

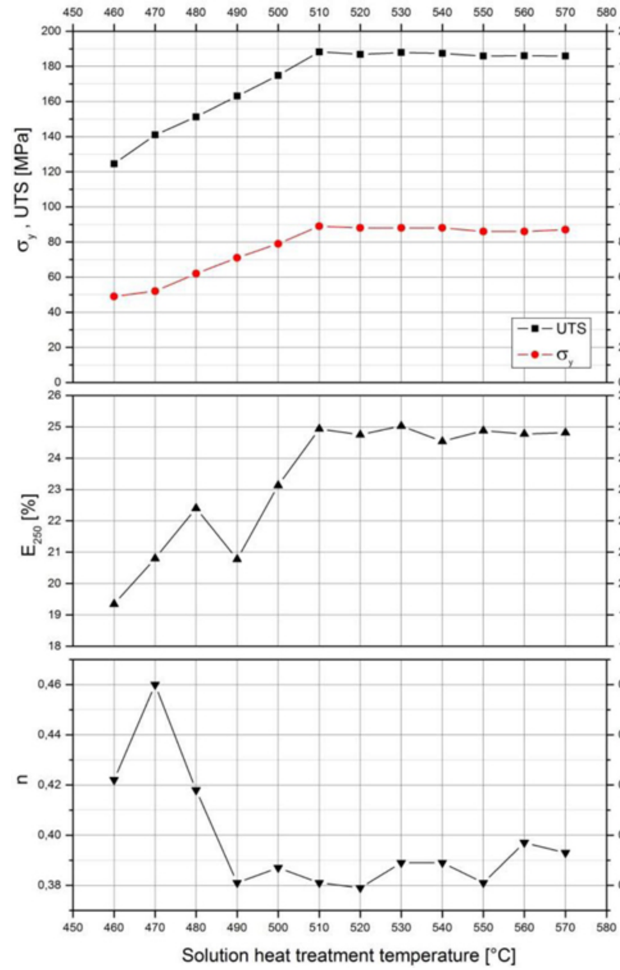

Figure 5. Ultimate tensile strength, yield strength, elongation to fracture and strain hardening exponent for *as-fabricated* rod solution heat treated at different temperatures.

mention that in order to be precise with elongation to fracture measurements, for each solution heat treatment temperature at least four rod samples were used. With respect to the strain hardening exponent *n*, it shows a constant value for all the samples treated at temperatures higher than 480°C. The strain hardening exponent is higher for the samples treated at lower temperatures, having a maximum in those samples treated at 470°C. According to the bibliography [12, 13, 14], the strain hardening exponent is related to the strengthening mechanism taking place, be it solute hardening, second-phase hardening, etc. According to this, it seems *a priori* that the strain hardening exponent is higher for a Mg_2Si precipitated microstructure than for a solution heat treated and naturally aged at room temperature for 4 days microstructure, even if the Mg_2Si precipitates are coarse. On the other hand, the yield strength for such a coarsely precipitated microstructure is much lower than that of the solution heat treated rod. Regarding the maximum of the strain hardening exponent at 470°C, its reason is not evident to the authors. Even though it was not the objective of this work to study the behaviour of the strain hardening exponent with respect to the different metallurgical states of the alloy, the authors found it worth mentioning these results.

Conclusions

Some conclusions can be drawn based on the results obtained. Firstly, there seems to be a minimum solution heat treatment temperature of 510°C. Temperatures above this minimum limit have no effect (neither positive nor negative) on neither the properties of the rod nor the drawn wire. Temperatures below 510°C not only lead to lower mechanical properties of the final product, but also lower the elongation to fracture of the rod, specially if the solution heat treatment temperature lies just below the *solvus* limit. Even though these detrimental effects are not big, they could lead to wire breaks during the drawing and/or stranding in high demanding processes. Also, the drop in the final mechanical properties could be a problem when tight specifications need to be met. It is thus recommended to assure a minimum solution heat treatment temperature of 510°C in the whole coil in order to assure an optimal solution heat treatment process. Regarding the strain hardening exponent with relation to the microstructure of the alloy in its different tempers, further work should be carried out in order to better understand the strengthening mechanisms acting on each case.

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