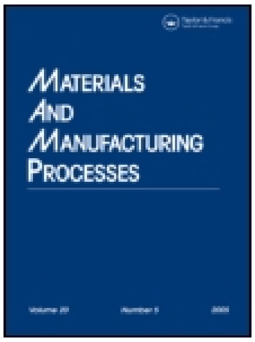

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Effect of Cryogenic Processing on Surface Roughness of Age Hardenable AA6061 Alloy

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The aging phenomenon in age hardenable aluminum alloys is complex and well under research. The supersaturated solid solution of these alloys, during aging, undergoes complex precipitation causing increase in strength with time. These alloys have wide range of applications in the aviation and automotive industry. The properties such as electrical conductivity and hardness of these alloys are well related to its precipitation behavior. Cryogenic treatment (CT) has been tried on tool and alloy steels where it has been found that this treatment positively affects the wear resistance and also causes uniformity in structure. The CT has become an important step in the manufacturing of tool steels.

This work comprises applying CT at −185°C to AA 6061 aluminum alloy for various time periods. The treatment was sequenced in the conventional solutionizing and artificial aging. This sequence of treatment has not been reported in the literature. The characterization was done using scanning electron microscopy. The behavior of this alloy to the treatment was identified by measuring electrical conductivity and hardness. The surface roughness of this alloy was also found to be highly influenced by this treatment.

Keywords Aging; Cryogenic; Conductivity; Hardness; Microstructure; Roughness.

Introduction

The effects of cryogenic treatment (CT) on various materials such as tools and alloy steels, copper electrodes, poly-tetra-fluro-ethylene are well under research in the last decade [1–7]. The increase in the wear resistance of tool steels due to CT is validated by many and being adopted in the tool and dies industry. The reasons for the changes occurring in tool steels due to CT are attributed to the precipitation of submicroscopic carbides in addition to the conversion of retained austenite to martensite. The conventional heat treatment of tool steels comprises hardening and tempering. CT can be given either at the end of the conventional treatment or as an intermediate treatment between hardening and tempering.

The hypothesis for the changes due to CT put forth by Huang et al. [8] refers to the "conditioning" of the matrix of the tool steels when they are subjected to the cryogenic temperatures. Later as the steel is subjected to tempering the conditioned matrix rejects the dissolved alloying elements causing their precipitation as carbides. The spatial contraction at the interface of the matrix and already present carbides (generation of dislocations) is also mentioned as one of the plausible causes.

The formation of supersaturated solid solution during solutionizing and quenching of age hardenable aluminum alloys of 2XXX, 6XXX, and 7XXX series and the precipitation reactions during aging [9] are very complex and several coherent precipitates form before the final equilibrium phase is produced –

$$2XXX : \alpha_{ss} \rightarrow\rightarrow \alpha + GP\text{–}I \rightarrow \alpha + GP - II \rightarrow \alpha + \Theta' \rightarrow \alpha + \Theta$$
$$6XXX : \alpha_{ss} \rightarrow\rightarrow \alpha + GP\ Zones \rightarrow \alpha + \beta'\ (Mg_2Si) \rightarrow \alpha + \beta\ (Mg_2Si)$$
$$7XXX : \alpha_{ss} \rightarrow\rightarrow \alpha + GP\ Zones \rightarrow \alpha + \eta'\ (MgZn_2) \rightarrow \alpha + \eta\ (MgZn_2)$$

The GP zones are ordered solute-rich group of atoms which produce appreciable elastic strains in the surrounding matrix. The diffusion for formation of these zones involves moment of atoms over short distances. Depending upon a particular alloy system, the rate of nucleation and the actual structure are highly influenced by the excess vacant lattice sites retained after quenching. A study [10] using atom probe field-ion microscopy has revealed that the intermediate precipitates formed during aging vary in composition further adding to the complex nature of their formation. The mechanical working prior to aging creates excess vacancies in the age hardenable aluminum alloys is a known phenomenon. This gives rise to the complex behavior of the precipitates in terms of extra precipitation, dispersion, and dissolution at different stages of aging [9, 11]. In case of CT at −185°C, the "conditioning" of the matrix is due to induction of residual stresses in the material, which further causes large number of fine precipitates in the material during tempering [7, 8, 12].

The point is that the changes due to CT are closely associated with the phenomenon of precipitation. Therefore it can be inferred that the alloys which are prone to

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the phenomenon of dissolution (austenitizing or solutionizing) and precipitation (during tempering or aging) should cause a change in their microstructures due to CT. CT, if applied between quenching and aging, should affect the changes in the alloy during aging. The "conditioning" mentioned above is also expected to take place during CT of AA6061 alloy to affect precipitation during aging. With this hypothesis the present work was planned.

There is a reference in the literature of a work by Luley et al. [13] about investigating the response of CT on AA 7075 age hardenable aluminum alloy. However the choice of treatment parameters in this work does not justify the outcome of the response. For example, the choice of holding period (soaking period) at cryogenic temperatures is of 48 h and 2 h, which appears to be a random selection. Recent work by Prabhu et al. [14] on a composite of an AA 6061-SiC and silicon carbides refers to some changes in the properties of this composite.

This work investigates the response of AA 6061 age hardenable aluminum alloy to the CT. The work comprises identification of changes in the microstructure by optical and scanning electron microscopy (SEM). Further characterization has been carried out by measuring the properties such as electrical conductivity, hardness, and surface roughness. The outcome clearly shows that there is a response of this alloy to CT with respect to various properties under certain treatment parameters.

EXPERIMENTAL SECTION

Samples of AA 6061 confirming to the composition by spectrometric analysis using ASTM B 308M-02a (as in Table 1) were cut from a plate by a wire electro discharge machine in the form of cubes having 250 mm sides. All these samples were first given T6 temper by heating them to 540°C, soaking for 100 min, and then quenching in water at room temperature. The specimens were further artificially aged at 160°C for 18 h.

HARDNESS

The hardness of all the samples was measured as per ASTM E18-03 on the Rockwell hardness tester on E scale, with 1/8th inch ball diameter, and 100 kg load.

SURFACE ROUGHNESS

All the samples were machined on a CNC vertical grinder with 0.5 mm as a depth of cut. The surface roughness was measured by a Mitutoyo make, Surftest SJ210, stylus tip radius 5 μm. Samples were machined with same cut and conditions before the measurement of roughness (R_a value) at different stages.

TABLE 1.—Composition of the AA 6061 used in this work.

Element	Si	Fe	Cu	Mn	Cr	Zn	Ti	Mg	Al
Wt. %	0.66	0.25	0.23	0.06	0.09	0.07	0.019	0.88	Balance

ELECTRICAL CONDUCTIVITY

Measurement of electrical conductivity at various stages of the treatment was carried out by Technofour-Indian make electrical conductivity meter (type 979) for nonferrous metals in % IACS to within 1% accuracy. It is a standard practice all over the world to express the conductivity of age hardenable aluminum alloys as %IACS (ASTM E1004-09).

IMAGING

SEM (SEM-JEOL 6380A, Japan) was used to image the specimen after metallographic polishing and etching with Keller's reagent.

CRYOGENIC TREATMENT

The CT was carried out in a cryogenic processor in which gaseous nitrogen at −196°C is introduced through a solenoid valve. The valve opening is controlled by a computer program so as to adjust the cooling cycle as per plan. In this work, the temperature controlled in the processor was −185°C due to some operating constraints. Two samples of AA 6061 were treated to T6 temper as in Fig. 1(a) as reference samples for comparison, and other batches of samples were solutionized, quenched, and immediately transferred to the cryogenic processor without any delay. Two samples each were subjected to the soaking period of 9, 12, 15, 18, 21, and 24 h, and then each pair artificially aged for 18 h at 160°C. The CT cycle is schematically shown in Fig. 1(b). It was assured that there is minimum lapse of time (few minutes) between any two consecutive treatments.

The soaking periods in the above experiment were decided on a similar pilot study that was carried out earlier by the authors as per the cycle shown in Fig. 1(b), with soaking periods (at −185°C) 12, 24, and 36 h. The measure deviation in the hardness values was observed between 12 and 24 h, and hence for the final experiment, the soaking periods were decided as mentioned above. CT, if given after T6 temper, showed negligible effect on the hardness and electrical conductivity of this alloy.

RESULTS AND DISCUSSION

Figure 2 shows the SEM images of AA 6061 at various conditions of treatment.

The images show the precipitates in the aluminum matrix for AA 6061 alloy. It can be noted that the CT has caused increase in the precipitates size. Typically much of the precipitate has disappeared for the sample which was given 15 h soaking period. These images clearly show the effect on the precipitation, dispersion, and dissolution behavior of the precipitates being affected due to introduction of the CT before conventional ageing cycle. However, no comments can be made on the characterization of the precipitates as it is kept out

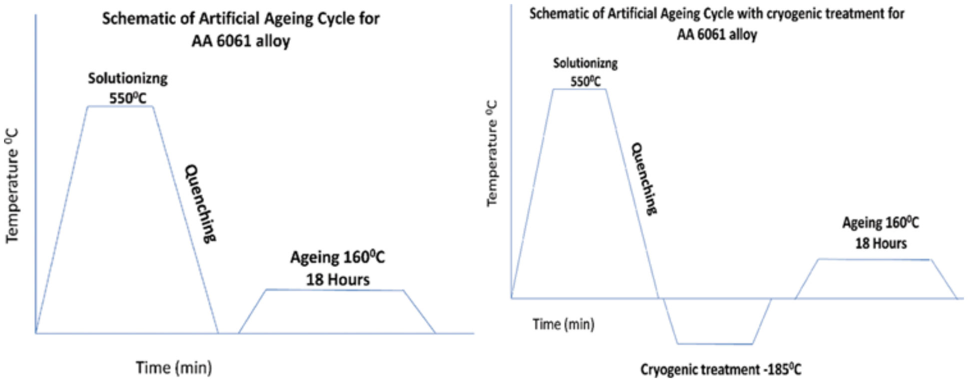
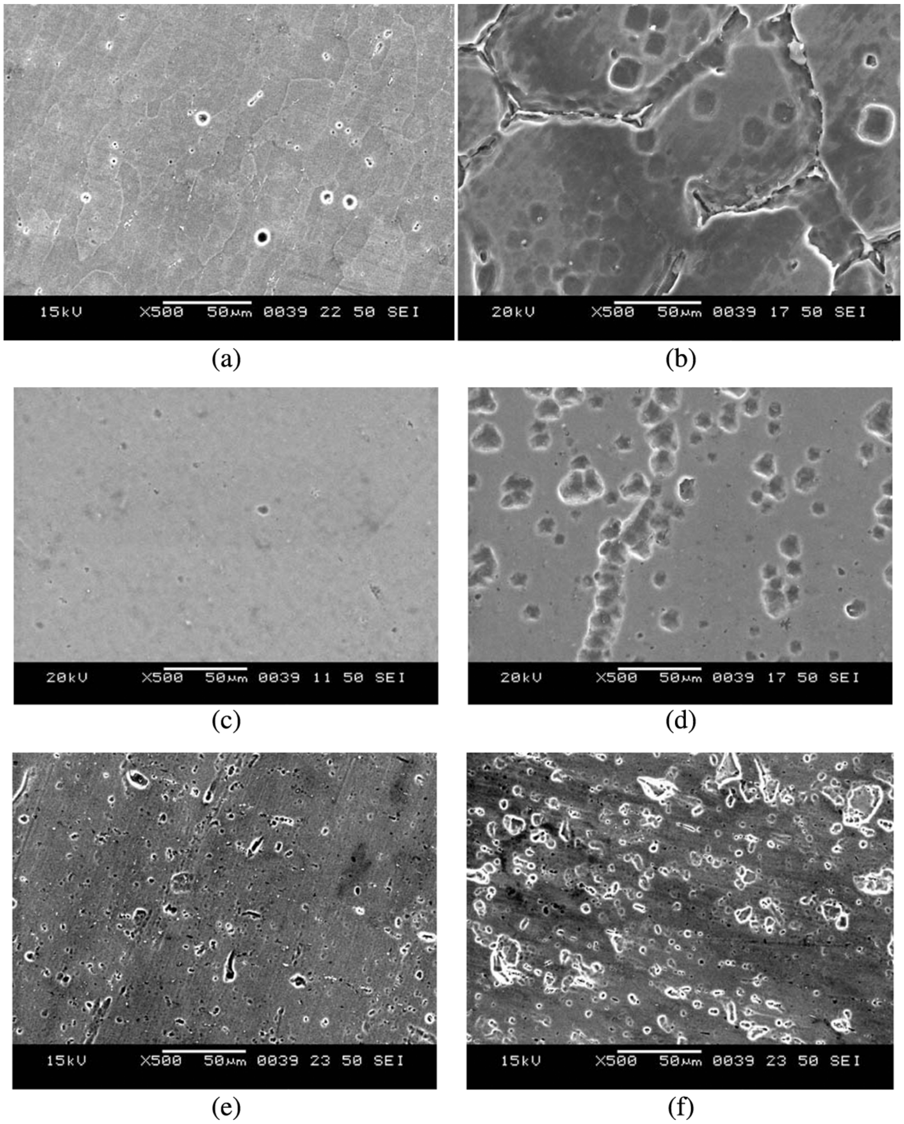


FIGURE 1.—(a) Conventional artificial aging cycle for AA6061 aluminum alloy; (b) Cryogenic cycle introduced in between quenching and aging treatment.



(a) (b)

(c) (d)

(e) (f)

FIGURE 2.—SEM images of AA 6061 under different conditions—(a) T6 temper; (b) Solutionizing + quenching + CT for 12 h; (c) Solutionizing + quenching + CT for 15 h; (d) Solutionizing + quenching + CT for 18 h; (e) Solutionizing + quenching + CT for 21 h; (f) Solutionizing + quenching + CT for 24 h.

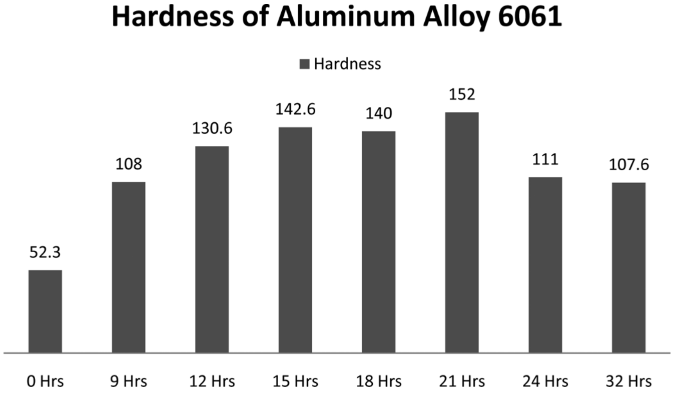


FIGURE 3.—A bar chart depicting effect of different soaking periods during CT on the hardness of AA 6061 and compared with its T6 condition.

of the scope of this work. However, this behavior is clearly reflected in the variation of hardness and electrical conductivity as shown in Figs. 3 and 4, respectively.

As shown in Fig. 3, the hardness is found to be increasing and attains higher values for the samples soaked between 15 and 21 h and decreases for higher hours of soaking period. If compared with the behavior of electrical conductivity, it can be seen that it also shows small increasing trend first but decreases for higher hardness values as the precipitation is in progress, and matrix is depleting in the alloying elements. Lowering of the electrical conductivity at higher hardness depicts dissolution of some of the precipitates. This typical behavior can be attributed to the phenomenon of dissolution and re-precipitation taking place due to CT. Therefore it can be conclusively said that the CT with soaking periods between 18 and 21 h causes three times rise in hardness of AA 6061 alloy. The effect of appearance of the vacant lattice sites after quenching seems to become more dominant due to CT, causing formation of large number of vacancies. This results in the formation of large quantities of fine precipitates causing three times higher hardness than in T6 condition.

The results of measurement of surface roughness of AA6061 (Fig. 5) for different soaking periods during CT also fall in line with the earlier results. Lower values of R_a for the samples soaked between 18 and 21 h indicate improvement in the surface roughness due to introduction of CT after quenching and before aging of AA 6061.

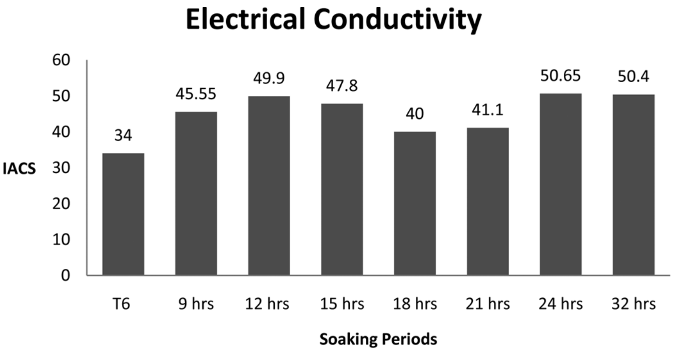


FIGURE 4.—A bar chart depicting effect of different soaking periods during CT on the electrical conductivity of AA 6061 and compared with its T6 condition.

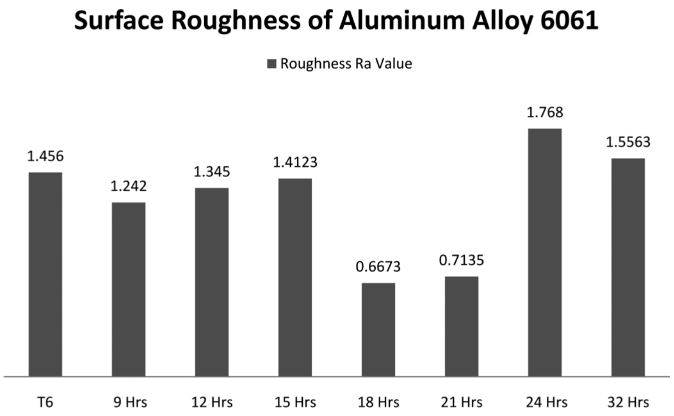


FIGURE 5.—Effect on the surface roughness R_a values of AA 6061 for different soaking periods during CT.

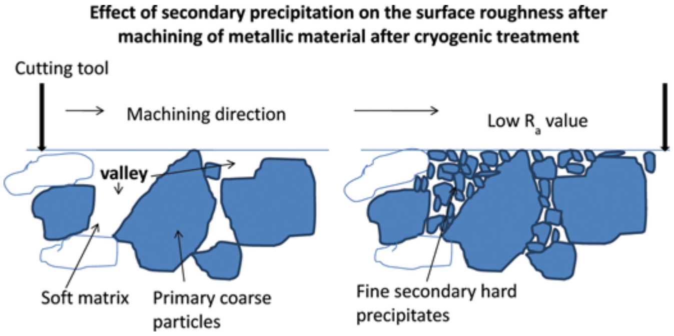


FIGURE 6.—A schematic showing improvement in the surface roughness due to secondary precipitation of the fine particles due to CT.

The earlier discussion of formation of large number of fine precipitates along with normal precipitation (as in T6 condition) causes improved surface roughness. This can be explained in terms of "filling up" of the gaps between coarser precipitates by the fine precipitates. Additionally uniform distribution of the precipitates due to CT is also known and mentioned by different investigators [1–6]. A hypothetical model for improvement in the surface roughness is shown in Fig. 6. This investigation has revealed an additional benefit of CT in terms of improvement in the surface roughness of an alloy.

This work was limited to mechanical characterization for the evaluating the effect of CT on an age hardenable aluminum alloy. Further investigations are required to study the precipitation behavior of this alloy by metallurgical characterization.

CONCLUSIONS

Based on the observations, it can be concluded that introducing CT (−185°C for 18–21 h soaking periods) between quenching and aging treatment in T6 temper of AA 6061 age hardenable aluminum alloy causes the following:

1. Very high hardness (almost triple) than the hardness obtainable in T6 condition.
2. Variation in the electrical conductivity indicating changes in the precipitation behavior of this alloy when compared with T6 temper.
3. Improvement in surface roughness of this alloy. This is a clear indication of getting a good surface finish after machining by subjecting this alloy to the CT.

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