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Effect of Modified Aging Treatments on the Tensile Properties, Quality Indices and Fatigue Life of Cast Components of Aluminum Alloy 354

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Abstract

With the drive to build higher performance automobile engines, there has been a steady demand to further improve the mechanical behavior of the cast aluminum alloy 354 through improvements in processing. The present study explores the possibility of improving the tensile properties, quality indices Q & Q_C and fatigue life of the alloy over those obtained by standard T61 treatment by adopting different modified aging treatments. These include i) lowering the artificial aging temperature ii) interrupted aging cycles similar to T6I4 referred to in the published literature and iii) artificial aging in two steps instead of in single step. Based on the results, a few modified aging treatments could be identified which lead to a comparable combination of tensile properties, but with improved fatigue life and a shade higher quality level.

Introduction

Aluminum cast alloy 354 based on the Al-Si-Cu-Mg system achieves high strength level after heat treatment. This is due to the presence of hardening elements copper and magnesium in the chemical composition. The high silicon content improves the castability of the alloy and reduces the shrinkage. Because of the excellent castability and the high strength levels to which the alloy 354 can be heat treated, it has an important place for structural applications in automotive sector. By adopting improvements in melting and casting practices and resorting to carefully designed Hipping and heat treatment of the cast components, the alloy 354 has been processed to high quality levels. Consequently, critical components such as Compressor wheels for turbochargers, requiring high level of mechanical properties - in particular the fatigue life - are made of this alloy.

The compressor wheel has an intricate shape and plays a vital role in the functioning of the turbo charger assembly. The compressor wheel turns out to be the weakest link in the assembly. This has been the driving force for continued researches aimed at improving the mechanical properties of alloy 354. The purpose of the present study is to examine if further enhancement of the tensile properties and fatigue life of 354 castings can be achieved by making changes to the standard aging treatment.

The normal practice has been to use the alloy in the T61 temper condition. The heat treatment process used to attain this condition involves the following stages:

- Solution treatment at 524°C ± 5°C for 6 hours (h) in the single α phase field in an electrical thyristor-controlled forced air batch furnace with high heating capacity to dissolve all the alloying (solute) elements and obtain supersaturated solid solution.
- Quenching in hot water (60 – 80 °C) to retain the supersaturated state; hold in hot water for about half an hour.
- Natural aging at ambient temperature for 8 h
- Artificial aging at 188 ± 5 °C for 5 h in a furnace with a relatively low heating capacity.

The specified mechanical properties for the T61 condition are shown in Table II. Also included in the Table are the mean values obtained after heat treating to this temper.

Detailed studies were carried out by Ammar et al [1] on the aging behavior of 354 aluminum alloy. In particular he studied the effect of artificial aging temperature on the tensile properties. They concluded that lower aging temperatures produce higher peak strength values, even though it takes longer time to attain the peak strength condition. There appears to be scope to try out artificial aging temperatures lower than that used for T61 treatment (188°C) and realize higher strength levels.

There is documented literature of the beneficial effect of T6I4 type aging treatments on the mechanical properties of a number of heat-treatable wrought and cast aluminum alloys [2-5]. After the standard solution treatment, artificial aging is carried out for a short period at a temperature close to the standard aging temperature with the expectation of attaining primary precipitation of at least one solute element. The material is then quenched and subjected to artificial aging for a long period at a relatively low elevated temperature. The treatment has been referred to as T6I4 in the literature [2-5]. Aging at relatively low aging temperature is supposed to promote secondary precipitation of solute elements and develop mechanical properties equal to or greater than the standard aging treatment. Studies relating to the effect of T6I4 treatment on the mechanical properties of 354 alloys are not available in published literature.

Artificial aging at two different temperatures - first relatively low and second at a higher temperature - can help in realizing a finer precipitate distribution and improved mechanical properties. This is due to the higher super saturation associated with a lower aging temperature. Tavitas-Medrano et al [6] have studied, among other things, the effect of conducting the artificial aging in two steps at two different temperatures on the mechanical properties of cast aluminum alloy 319 and 319 with 0.4% Mg. The effect of carrying out artificial aging at two different temperatures (in two steps) on the mechanical properties obtained has not been studied on 354 alloys.

The present study explores the possibility of improving the mechanical properties of alloy 354 by adopting modified aging treatments in line with the foregoing discussion.

In the recent years, the concept of quality index has been increasingly used for characterizing the quality of cast aluminum alloys [7-11]. The concept is based on the fact that the quality of aluminum alloy castings may be defined using numerical values which correlate to their tensile properties. The current study also investigates the influence of the various modified aging treatments on the quality index values of 354 castings. Two quality indices have been adopted in the present study, Q and Q_C. The quality index Q was proposed by French researchers [9] and takes into account the ultimate tensile strength (UTS) and elongation to facture (E_f) and has been widely used as a measure of the relative quality level of cast aluminum alloys.

$$Q\ (\text{MPa}) = \text{UTS}\ (\text{MPa}) + k.\log_{10}(E_f) \qquad ....$$ ①

Where K is a material constant and taken as 150MPa.

The quality index Q_C is proposed by Caceres and coworkers [10-11] and is calculated using the equation.

$$Q_C\ (\text{MPa}) = \text{UTS} + 0.4(\text{YS})\ [E/a(\text{YS})]^n \log_{10}(E_f) \qquad ....$$ ②

Where E is the young's modulus, a is scale factor of the order 1 and n, the Strain hardening exponent at room temperature. The value of n is taken as 150Mpa for most Al-Si-Cu-Mg alloys.

The indices Q and Q_C have been chosen for use in the present study as they can be readily calculated from the available tensile test results. The index Q has been widely used by previous workers to do quality rating of cast aluminum alloys. In particular, Ammar et al [1] have used it to evaluate the effect of aging temperature and time on the quality of cast alloy 354. Use of Q_C in addition is in the context of the limitation of Q in that it is not a function of YS of the material

In the present study, statistical treatment of the fatigue life data obtained from the tests has been carried out using a 2-parameter Weibull analysis.

The total fatigue life in cast aluminium alloys can be estimated by integrating the Paris-Erdogan Law [15,16] where initial crack length was taken as the pore size measured on the fracture surface. These studies indicate that fatigue life depends strongly on the initiating pore size. The pores can act as sites for early nucleation and propagation of cracks. So, it is logical that closing these pores will lead to increase in the fatigue life of the material.

2. Methodology

2.1. Melting & casting:

The alloy was received in the form of ingots. An electrical resistance furnace with 500 kg capacity SiC crucible was used for melting. The melting temperature was maintained at 740°± 5°C by thyristor power control. Degassing was carried out using dry nitrogen injected into the melt by means of a rotating graphite holder. Modification was done using Al-10 % Sr master alloy; grain refinement was carried out through additions of 5 % Ti-1 % B-Al master alloy. Liquid metal was poured into dried molds made of plaster of Paris. The castings were knocked out of the molds, shot blasted and taken up for heat treatment. The plaster of Paris mold baked at 220°C was casted with the metal ready for pouring by counter gravity process [12-14].

Table I. Mean chemical composition of the alloy 354 (in Wt. pct.)

Si	Cu	Fe	Mg	Mn	Zn	Ti	Ni	Pb	Cr	Sn	Al
9.0	1.69	0.08	0.53	0.04	0.003	0.16	0.04	0.001	0.002	0.002	Bal.

The micro structure and XRD patterns of as cast condition are shown in Fig.1 (a) and Fig.1 (b) respectively.

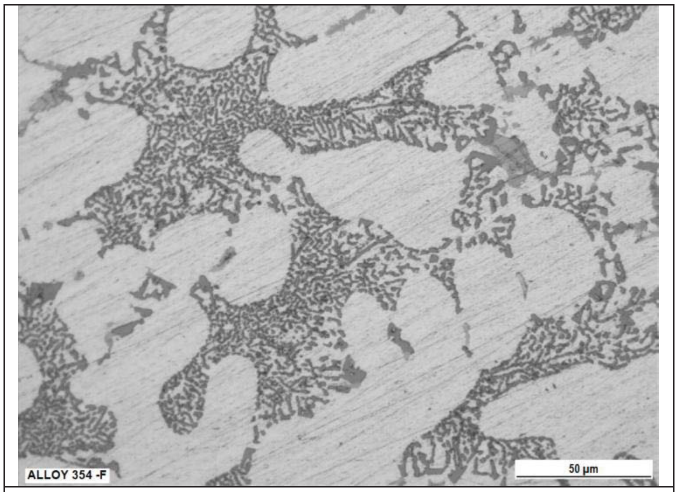

Fig.1(a). Microstructure in as-cast condition

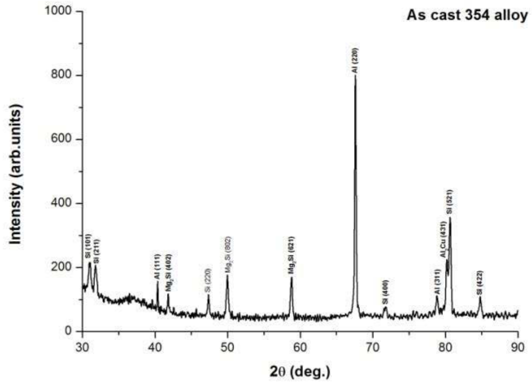

Fig.1(b). XRD pattern of as-cast condition

2.2 Hipping and heat treatment

For some applications, the castings were subjected to a Hipping process consisting of holding at a high temperature in an inert nitrogen atmosphere for a specified period of time at a constant pressure. The hold temperature was lower than the solution treatment temperature. The paper deals with studies carried out on Hipped castings.

The microstructure and XRD patterns in heat treated condition are shown in Fig.2 (a) and 2 (b) respectively. The fragmentation and spherodization of eutectic silicon exist while heat treated. The XRD shows the dissolution of equilibrium phases such as Mg_2Si and Al_2Cu phases due to fine distribution compared to the as cast condition which reveals scattering of precipitates.

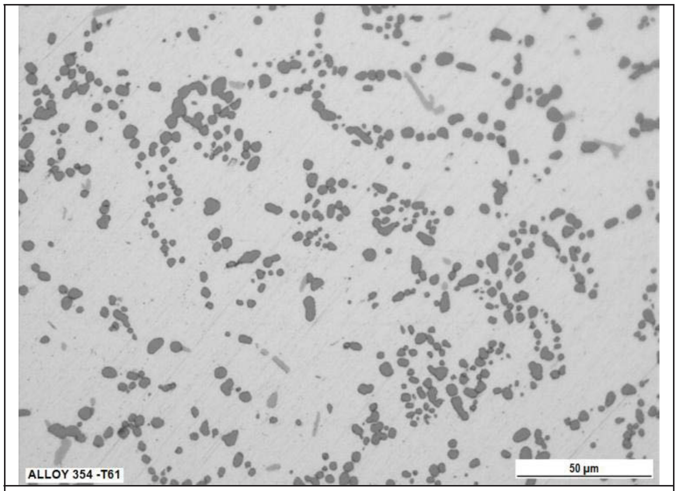

Fig.2(a). Microstructure in heat treated condition

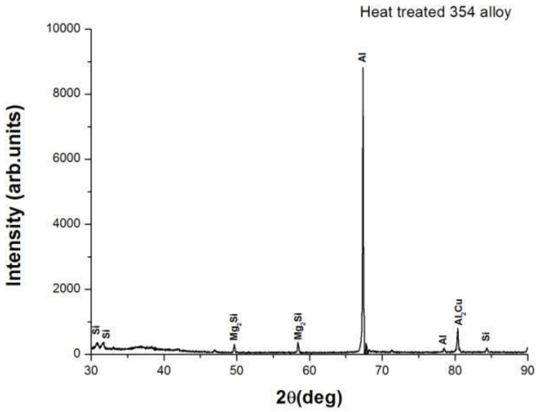

Fig. 2(b). XRD in heat treated condition

Table II. Mechanical properties of the alloy 354 in T61 condition

Property	UTS	YS	E_f	Hardness
	[MPa]	[MPa]	[%]	[BHN]
Specified	370 min.	270 min.	5 min	90 – 140
Mean	405	310	7.9	130

2.3 Modifications carried out to the standard aging treatment.

2.3.1. Varying aging temperatures:

In the present study, artificial aging was carried out for 5 h at 188°C, the temperature used for the standard T61 treatment, and three other temperatures – 177, 171 and 160 °C. Figure 3 shows the heat treatment cycle schematically. Tensile testing was carried out after artificial aging.

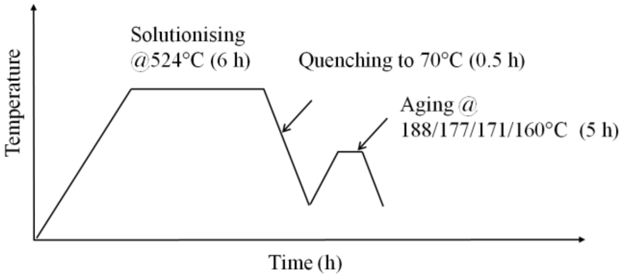

Fig. 3. Schematic of heat treatment cycle with varying artificial aging temperature

2.3.2. T6I4 Treatment:

In the present trials, 0.5 h of dwell at a temperature of 188 °C has been chosen for the primary precipitation. A temperature of 100 °C is chosen for the secondary precipitation. Mechanical properties were monitored after various times of dwell at the secondary precipitation temperature (1/11/36/86/186/386 h). Figure 4 shows the heat treatment cycle schematically.

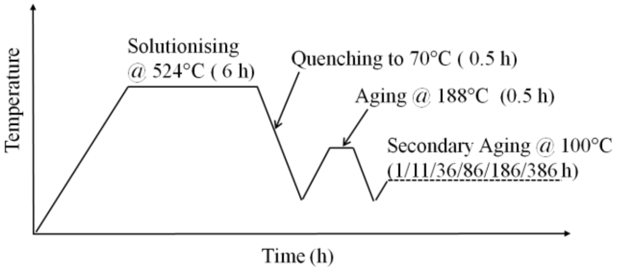

Fig 4. Schematic of T6I4 heat treatment

2.3.3. Artificial aging in two steps instead of in single step:

In the present study, the castings are aged without natural aging in two steps as follows:

Aging at 170 °C for 1/2/5 h after aging at 100 °C for 2 h
Aging at 170 °C for 1/2/5 h after aging at 100 °C for 5 h

Mechanical properties at the end of the two-step heat treatment have been evaluated and compared with those obtained after the standard aging treatment. Figure 5 shows the heat treatment cycle schematically.

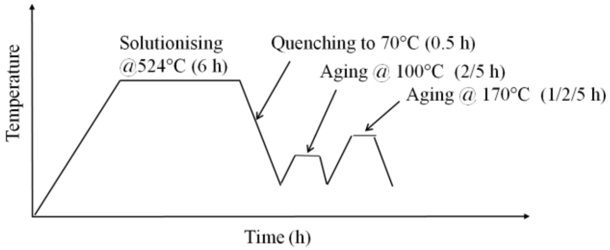

Fig. 5. Schematic of heat treatment cycle involving two step aging

2.4. Hardness and tensile testing:

Brinnel hardness was measured directly on the castings using 10 mm ball indenter and 1000 kg load. Measurements in each condition were done on three to five castings. The hardness numbers reported here are average values.

Instron make machine was used for the tensile testing. The coupons for testing were extracted from the rear face of the casting. For each of the heat treatment conditions, extraction was done from three to five castings. The results reported here are the average values.

2.5 Quality Indices:

The Q & Q_C values are calculated as described in the equation (1) & (2) based on the numerical values monitored after the test bar tested in the tensile testing machine.

2.6. Fatigue Life Testing:

The samples are derived from the back face of compressor wheel in the form of disc. The samples are machined in such a way that the stress level acts uniformly throughout the contour which is about 260MPa. The samples are tested on cyclic load between 20 & 200Kgs at constant 0.1 R value. The characteristic fatigue life 'η' and Weibull modulus 'β' are evaluated from the fatigue testing on no. of cycles 'N'. Two parameter analysis has been carried out on Weibull analysis and the plot is considered having good fit if square of linear correlation $(\rho^2)>0.95$ [17, 18].

3. Results

3.1. Varying artificial aging temperatures:

The aging temperatures @ 177 & 171°C shows the peak aged condition in achieving higher YS, UTS & small dip in elongation. However the quality indices Q & Q_C has shown clearly from the mechanical properties correlation that leads to higher quality indices over standard aging @ 188°C. The aging temperature @ 160°C shows the least mechanical properties and quality indices which may be due to under aged condition. There may be possibility for achieving higher mechanical properties @ 160°C aging temperature if the time of dwell can be taken higher than 5h to reach peak aged conditions as stated by Ammar et al [1].

Table III Tensile test results and quality indices as a function of artificial aging temperature

Artificial aging temperature	YS [MPa]	UTS [MPa]	E_f [%]	Q [MPa]	Q_C [MPa]
188	310	409	8.6	549	509
177	333	456	8.4	595	561
171	325	451	8.4	590	554
160	283	415	10.2	566	516

3.2. T6I4 Treatment:

The hardness was found to be monotically increasing with report to the dwell @ 100°C aging. The Mechanical properties were monitored at each dwell and the properties were higher for 86h. There was a dip in UTS and YS at a cumulative hold time of 11h.Quality indices also acknowledge that there is improvement of mechanical properties compared to the standard aging.

Table IV. Mechanical properties and quality indices of T6I4 aging.

Time of secondary aging [h] @ 100°C	Hard-ness [BHN]	YS [MPa]	UTS [MPa]	E_f [%]	Q [MPa]	Q_C [MPa]
0	116	250	386	11.8	547	483
1	128	266	393	12.0	555	495
11	133	265	389	8.5	529	477
36	140	271	401	10.3	553	499
86	141	298	421	8.8	554	519
186	140	294	417	8.3	554	511
386	145	281	410	9.1	543	505

3.3. Artificial aging in two steps instead of in single step:

Within the realm of present study on two step artificial aging, the highest hardness, UTS values are obtained after 5h of aging @ 100°C followed by 5h of aging at 170°C. Hardness value increases @ 170°C after aging @ 100°C irrespective of aging time. It was also properties were showing higher UTS & Ef values compared to standard aging @ 188°C for 5h.

Table.V. Mechanical properties and quality indices of two step aging temperatures

Details of 2-step ageing	Hardness [BHN]	YS [MPa]	UTS [MPa]	E_f [%]	Q [MPa]	Q_C [MPa]
2 h at 100°C + 1 h at 170°C	112	251	395	11.6	555	492
2 h at 100°C + 2 h at 170°C	119	266	389	10.7	543	487
2 h at 100°C + 5 h at 170°C	130	295	407	8.6	547	503
5 h at 100°C + 1 h at 170°C	114	237	378	12.5	543	473
5 h at 100°C + 2 h at 170°C	133	262	392	11.0	548	489
5 h at 100°C + 5 h at 170°C	138	300	416	8.5	555	513

3.4. Fatigue life testing:

The tested samples are plotted in the Weibull analysis and the parameters 'β' & 'η' are evaluated for the various modified aging treatments. The plot for higher mechanical properties and quality indices obtained in each aging treatment are evaluated and the Table VI. shows the 'β' ,'η' and ρ^2 of fatigue life testing.

Higher ‘η’ is the number of cycles at which 63.2% of components fail and higher ‘β’ represents then scattering [18]. The ‘η’ value is high in two step aging of 5h @ 170°C after 5h @ 100°C compared to standard aging @ 188°C for 5h and other variations. However the ‘β’ value of 188°C aging is higher than other variants tried out here. But the designers look forward for β and η to find out the suitable treatment relevant for their application.

Table.VI. Fatigue life – Results of two-parameter Weibull analysis for different aging treatments

Details of aging treatment	*B*	*η*	ρ^2
At 188°C	*7.50*	*1.38 E + 5*	*0.97*
At 171°C	*5.65*	*1.40 E + 5*	*0.99*
T6I4 (interrupted)	*5.36*	*1.61 E + 5*	*0.93*
Two Step	*3.90*	*1.98 E + 5*	*0.97*

4. Discussion

4.1. Varying artificial aging temperatures:

The results show that the aging at 177°C for 5h was obtained higher tensile properties followed by 171°C. This is due to peak aged at this variant where the hardening takes place and subsequently over aged at standard aging and under aged at 160°C are also found. There is significant increase in yield strength, UTS and elongation monotonically at 177 and 171 °C. Thus there is an advantage of varying aging temperatures to find out the mechanical behaviour of peak aged condition and the quality indices again confirms that the 177°C was found to be optimized aging temperature.

4.2. T6I4 treatments:

Highest strength levels were obtained after 86h of hold at 100°C. The Q & Q_C was obtained after the hold time of 86h due to higher UTS & E_f compared to standard aging. However YS value is lower than the value after standard aging cycle.

4.3. Artificial aging in two steps instead of in single step:

Best YS & UTS values were obtained after 5h of aging at 100°C followed by 5h of aging @ 170°C. The UTS and Ef values after this treatment are a shade better than those after standard aging cycle. This study offers commercially attractive in industry due to short aging time in two step aging. Q & Q_C values are also shows higher than those after standard aging.

4.4. Fatigue life testing:

The fatigue plot is shown in fig.6. and indicates that the two step aging gives higher fatigue life compared to other modified aging treatments carried out The T6I4 aging & 171°C aging follows subsequently in the plot. It has been noted that the standard aging and 171°C aging has one point with less no. of cycles @ 95% confidence level with respect to two step aging and T6I4 aging.

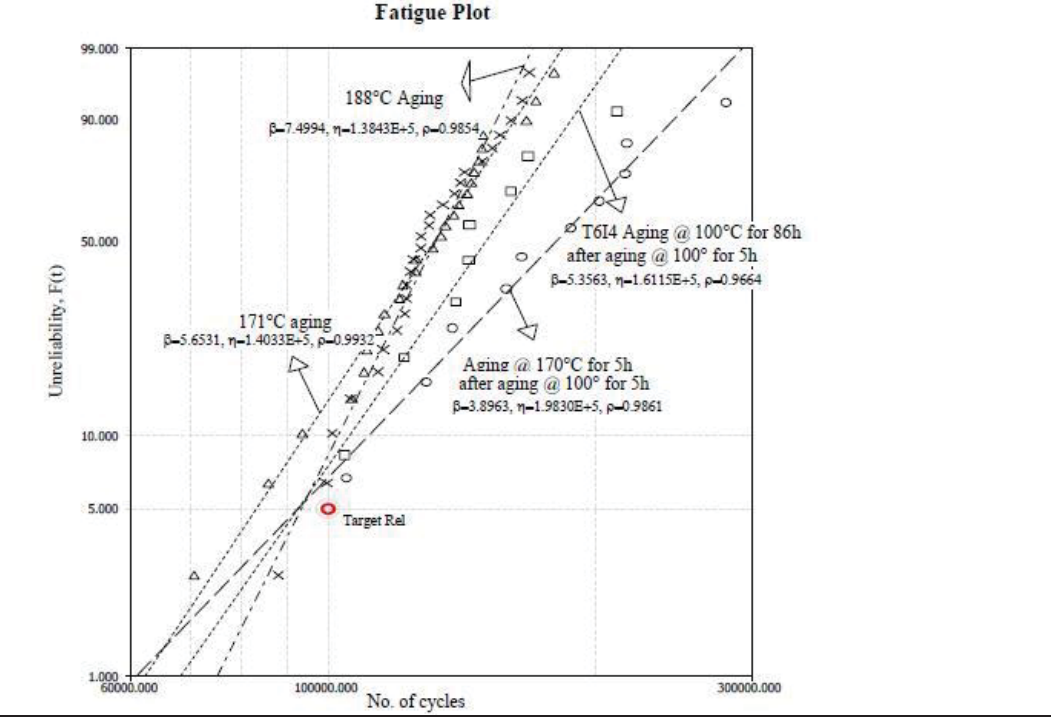

Fig.6 Fatigue plot for various modified aging treatments

5. Conclusions

- Several modified aging treatments have been tried out on compressor wheel castings of aluminum alloy 354.

- Decreasing the artificial aging temperature from the 188 °C used for the standard T61 temper to 171/177 °C leads to (i) improved strength with essentially no reduction in ductility and (ii) higher values of the quality indices Q and Q_C. There is thus a strong case for a reduction of artificial aging temperature to improve the mechanical behavior.

- A T6I4 treatment with 86 h of hold at secondary precipitation temperature of 100 °C results in tensile properties comparable to those obtained after standard aging; in addition, the quality indices Q and Q_C are a shade higher and fatigue life also appears to be higher This treatment is hence of interest to the technologist.

- The 2-step artificial aging treatment comprising of 5 h at 100 °C followed by 5 h at 170 °C gives tensile properties comparable to those obtained after standard aging treatment and in fact the Q and Q_C values are a shade better. In addition, the characteristic fatigue life is almost one and half times that in the standard T61 condition. This treatment also is hence of interest to the technologist.

- Quality indices Q and Q_C taken together appear to serve a useful purpose in selection of aging treatment for improving the mechanical behavior of the alloy 354.

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