

Correlation of Strength with Hardness and Electrical Conductivity for Aluminium Alloy 7010

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Abstract The tensile strength, proof strength, hardness and electrical conductivity of Al alloy 7010 under different temper and ageing conditions were investigated with the aim to correlate strength with hardness and electrical conductivity so that the strength of the alloy can be determined non-destructively. Following the solutionising treatment, continuous age hardening was performed on a series of test coupons, taken from a large plate, to produce a wide range of precipitation hardening conditions, which gave rise to progressive variations of strength, hardness and conductivity. The relationship between strength and hardness was found to be reasonably linear, whereas the relationship between hardness and strength with electrical conductivity was non-linear. The ageing conditions and therefore the mechanical properties of the components can be predicted more accurately by the simultaneous combination of hardness and conductivity values.

Introduction

Al alloy 7010 in the T7651 temper condition is primarily used in the aircraft industry for the manufacture of structural components, because of its high strength coupled with high resistance to stress corrosion cracking and good fracture toughness. The prediction of strength for many Al alloys has been researched for many years by modelling or by correlating it with non-destructive measurements of hardness and electrical conductivity. For example, the quench factor analysis model has been applied successfully to the prediction of post-quench physical properties in aged Al alloys [1]. Starink and Wang [2] reported a model for predicting the yield strength based mainly on microstructural data, which could predict proof strength with accuracy of 14 MPa. Due to their accuracy and fast response, non-destructive measurements of hardness and electrical conductivity have also been used to study the age hardening process and the associated precipitation mechanism in many heat treatable Al alloys. Rosen *et al* [3] used electrical conductivity to study the changes in the mechanical properties during the age hardening process in AA 2024 and evaluated quantitatively the extent of removal of the minor constituents Cu and Mg from the solid solution. Tiryakioglu *et al* [4] studied the strength-hardness relationship for Al-7wt% Si alloys with different levels of Mg. Both yield and tensile strengths are found to change linearly with Mayer hardness. Brasche *et al* [5] and Koch and Kolijn [6] also studied the properties, such as strength, fracture toughness and stress corrosion cracking, non-destructively.

The accurate prediction of static strength for AA 7010 using non-destructive measurements of hardness and electrical conductivity becomes important when this heat treatable AA is exposed to overheating. Overheated AA 7010 in temper condition T7651 exhibits decreases in electrical conductivity and hardness, indicating a loss of strength. At present, the prediction of strength losses

from corresponding values of electrical conductivity and hardness is difficult due to lack of data available in the public domain. The loss of strength as indicated by lower electrical conductivity and hardness suggests that some of the strengthening alloying elements in the precipitates have been re-dissolved back into the solid solution during overheating. The effect is consistent with the fact that all metallic additions to Al reduce its electrical conductivity, and these additions in solid solution depress the electrical conductivity to a greater extent than when out of solution [7].

Therefore the correlation of strength with hardness and electrical conductivity is essential to gain understanding of the degree of strength loss and thus provide an accurate assessment of the areas affected by overheating. This exploratory investigation intends to address this shortfall and to gain an understanding of the metallurgical phenomena, with an aim to improve the manufacturing efficiency of structural aircraft parts. The correlation of hardness and electrical conductivity with static strengths for AA 7010 is performed on the full range of temper conditions of natural ageing, artificial ageing and over ageing. It is envisaged that this data could be used to determine non-destructively, the strength of the material as well as the unknown thermal history of a given suspected area of an aircraft component.

Material and Experimental Methods

The composition of the AA 7010 assessed in this investigation is shown in Table 1. The material was supplied as a plate (3403×1320×157 mm), which was manufactured from a slab by a complex thermo-mechanical process. A number of cross sectional slices (5.0 mm thick) were cut from one end of the plate perpendicular to the rolling direction. Each slice was further cut into five strips of equal width, each representing a different depth through the plate thickness. Flat tensile test specimens were manufactured from the strips to the dimensional requirements of British Standard BS 4A-4. They have a gauge length of 50 mm, a minimum parallel length of 63 mm, a minimum transition radius of 25 mm, a width of 12.5 mm and a thickness of 3 mm.

Table 1 Chemical composition of AA 7010

Element	Zn	Mg	Cu	Zr	Fe	Si	Ti	Ni	Al
Wt %	6.30	2.34	1.75	0.12	0.05	0.04	0.032	0.01	Rest

The tensile test specimens were re-solutionised at 475°C for 50 minutes in a Caltherm air circulating furnace, quenched in water (~ 22°C) at a quenching rate of about 95°C/s, and then frozen to -18 °C for subsequent treatments. The full treatment cycle was: natural ageing at room temperature for more than 120 hrs; artificial ageing at 120°C for 10 hours followed by 173°C for 8 hrs to attain T7651 condition; and over ageing at 173°C for 100 hrs. Most of the specimens did not go through the full cycle though. The specimens were removed at different time intervals in different stages of the full cycle. A wide range of temper conditions was obtained by varying the soaking times of natural ageing, artificial ageing and over ageing. The natural ageing times ranged from 0.25 hrs to 16 days. The artificial ageing times ranged from 15 minutes to 10 hrs at 120 °C and from 15 minutes to 108 hrs at 173 °C.

The hardness and electrical conductivity measurements of the specimens were performed on a surface polished to approximately 1.5 µm prior to the tensile tests. The hardness was measured by a Vickers HTM8313 hardness tester with a 5 kg load. The electrical conductivity was measured by a Forster SIGMATEST EC2.068 electrical conductivity meter, based on the eddy current principle. The tensile tests were carried out using an Avery Denison testing machine, Model 6157, with a load capacity of 100 KN, according to British Standard B.S. EN 10002-1.

Results

Fig. 1 shows the age hardening profile of AA 7010, where hardness and electrical conductivity vary progressively with natural ageing, artificial ageing and over ageing. Although the natural and over ageing sections show a nearly linear correlation, the overall relationship between hardness and electrical conductivity is not linear. It is therefore impossible for either of these variables to be predicted from another without additional information.

In the natural and over ageing conditions, electrical conductivity and hardness showed a reciprocal effect, i.e. an increase in one produced a decrease in the other and vice versa. The hardness increased from 78 to 147 Hv during natural ageing and from 147 to 192 Hv during artificial ageing, and decreased from 192 to 120 Hv during over ageing. The electrical conductivity decreased with natural ageing from 18.27 to 15.78 MS/m, then increased with artificial and over ageing from 15.78 to 25.81 MS/m. In the artificially aged condition, an overall increasing trend for both hardness and electrical conductivity was registered. In the initial stage of artificial ageing, there is a small decrease in hardness from 147 to 118 Hv and an increase in electrical conductivity.

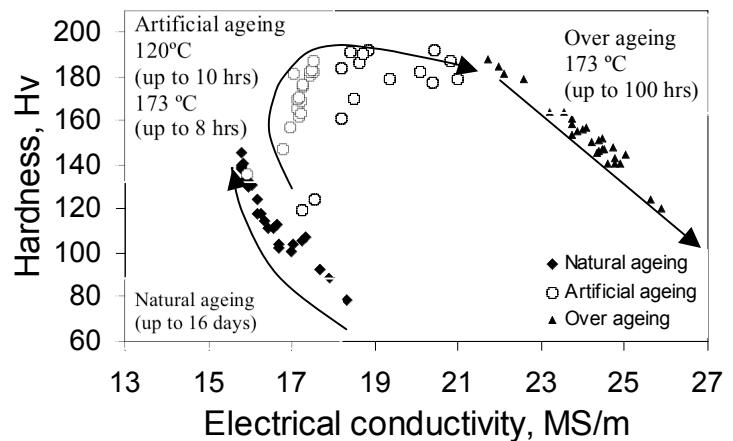


Fig. 1 Hardness and electrical conductivity profile of AA7010 at different stages of ageing treatment. The progress of ageing with temperature and time is indicated

Fig. 2 shows the correlation of strength with hardness for all three temper-conditions of natural ageing, artificial ageing and over ageing. The graph shows a linear relationship of hardness with ultimate tensile strength (UTS), with the correlation coefficient, R^2 , of 0.9729, suggesting a good correlation. On the other hand, the correlation of 0.2% proof strength (PS) with hardness gives a lower R^2 of 0.8858, indicating more pronounced scattering. Fig. 2 also shows different gradients of 3.7162 and 2.4664 for PS and UTS respectively.

Fig. 3 shows the variation of strength ratio (PS/UTS) with hardness. For a given value of hardness, the strength ratios for temper conditions below peak strength (natural and artificial ageing) and for the over aged condition are different. The over aged conditions gave a higher strength ratio than the under aged.

Fig. 4 presents a non-linear correlation of strength ratio with electrical conductivity up to a value of approximately of 20.4 MS/m at the onset of over ageing and a linear correlation in the over aged condition.

Fig. 5 shows the relationship between elongation and hardness. In the naturally aged and artificially aged conditions, elongation decreased with increasing hardness. In the over aged condition, the hardness decreased and the elongation stayed at a lower level, indicating a loss of ductility.

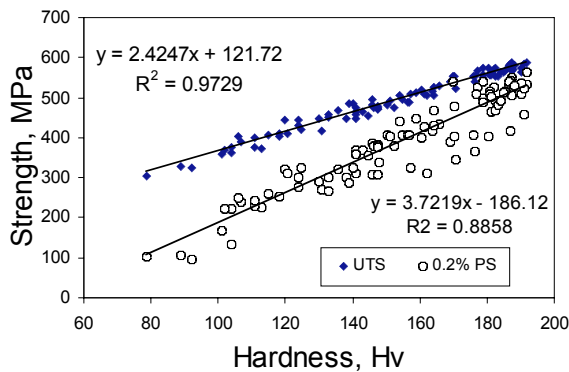


Fig. 2 Relationships of UTS and 0.2% PS with hardness.

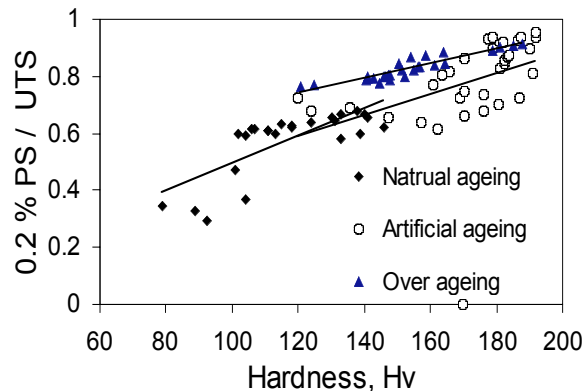


Fig. 3 Correlation of strength ratio (PS / UTS) with hardness in different ageing conditions

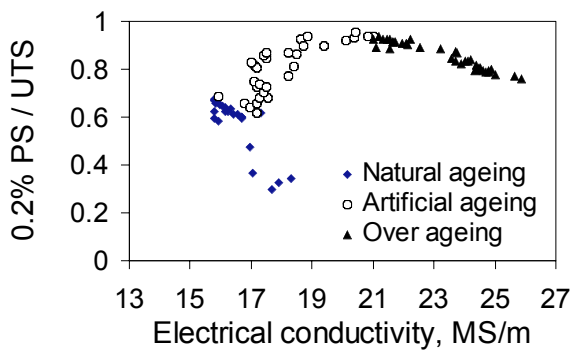


Fig. 4 Correlation of strength ratio (PS/UTS) with electrical conductivity in different ageing conditions

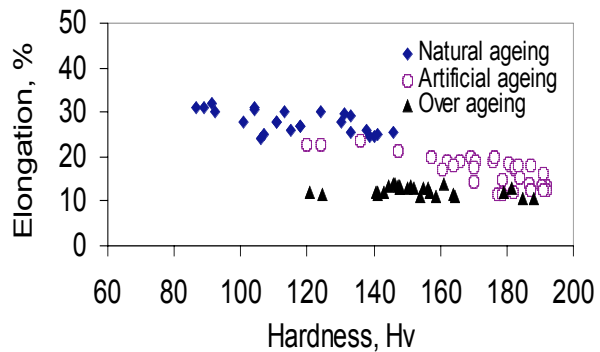


Fig. 5 Correlation of elongation with hardness in different ageing conditions

Discussions

All known metallic additions to Al reduce its electrical conductivity, and these additions in solid solution depress the conductivity to a greater extent than when out of solution. The electrical conductivity is therefore largely determined by the amount of alloying elements in the solid solution and the amount and nature of precipitates. The non-linear correlation of electrical conductivity with hardness/strength (Fig.1) is the result of the differences in response of electrical conductivity and hardness with ageing hardening. These are inherent from the nature and size of precipitates and their intermediate products, which had formed at various ageing stages. Koch and Colijn [6] also reported a non-linear relationship between strength and electrical conductivity for AA 7075

The steady decrease of electrical conductivity during natural ageing for many solution treated Al alloys has been attributed by many investigators as a result of gradual increase in the number and size of a very fine and coherent precipitates, called G.P. zones. It has been well documented that the G.P. zones are very effective in scattering electrons, leading to the decrease in the electrical conductivity of the matrix. This electron scattering effect is induced by the coherent strains associated with the G.P. zone precipitates. For the alloy under investigation, the diffusion of Zn, Mg, and Cu solute atoms from the solid solution to form the G.P. zone precipitates causes a purification effect of the matrix, a consequence of which is an increase of electrical conductivity.

However, the overall decrease in electrical conductivity observed on the natural ageing region (18.27 to 15.78 MS/m) is due to a more predominant electron scattering effect of the G.P. zones.

During natural ageing, the hardness is largely determined by the amount of fine precipitates formed in the alloy; more fine precipitates lead to higher hardness. The increasing trend of hardness at room temperature (from 78 to 147 Hv) can be summarised as the product of a progressive increase of internal stresses due to strains around the G.P. zones and the precipitates themselves, which hinder the movement of gliding dislocations. Chemical hardening also contributes to the increase of hardness or strength of the aged aluminium alloys, but to a less extent.

The initial drop in hardness from 147 to 118 Hv and the respective increase in electrical conductivity at the beginning of the artificial ageing (Fig. 1) is believed to be inherent from a retrogression effect or a dissolution effect of some of the already formed G.P. zones, which are no longer thermodynamically stable at 120°C. The overall increase of electrical conductivity and hardness in the artificial ageing region can be attributed to the formation of the coherent and semi-coherent precipitates (MgZn_2) and their intermediate precipitates. The alloying elements (Zn, Mg and Cu) precipitating out from the solid solution increase the electrical conductivity due to the purification effect of solute atoms from the matrix, as the precipitates formed have been reported to be less effective in scattering the electrons than the G.P. zones. The hardness increase is mainly due to the lattice strain hardening, caused by the precipitation of coherent and semi-coherent precipitates.

The progressive increase in electrical conductivity and drop in hardness in the over ageing region are due to the formation of incoherent precipitates. The over-ageing of Al alloys has generally been accepted to start when the intermediate or fully formed precipitate starts to become incoherent with the matrix and the internal lattice strains are lost. As over-ageing progresses, the precipitates increase in size, become less numerous and lose coherency with the matrix. The overall effect of this is a continuous loss of hardness and an increase of electrical conductivity. When full over ageing or annealing condition is attained, further precipitation of alloying elements from the solid solution is not possible and the final equilibrium precipitate structure (MgZn_2) is attained. The hardness and electrical conductivity attained for the most extreme case of over ageing (120 Hv and 25.81 MS/M) indicate that the equilibrium precipitate (MgZn_2) was not attained.

The good linear relationship between UTS and hardness with a high regression R^2 value of 0.9728 (Fig. 2) suggests that the prediction of UTS for a given hardness value can be made with a reasonable degree of accuracy, within 95% confidence. On the other hand, the prediction of 0.2% PS is less accurate due to a lower R^2 value (0.8828). Similar correlation between hardness and strength for AA 7075 was also reported by Koch and Kolijn [6]. Different temper conditions may give a similar hardness but different ductility and in turn different 0.2% PS values as a result of the different strain hardening characteristics. However, the PS/UTS ratio varies nearly linearly with hardness in both the under-aged and over-aged temper conditions, although with different gradients, as shown in Fig. 3. The 0.2% PS can therefore be predicted more accurately by combining hardness and electrical conductivity values. Specifically, the likely temper condition can be determined by examining both the hardness and electrical conductivity values from Fig. 1. With the temper condition known, the UTS and the strength ratio, and thus the 0.2% PS, can be determined from the hardness value.

Conclusions

In the full range of temper conditions for AA 7010, there is a non-linear correlation of electrical conductivity, hardness and strength. For a given pair of hardness and electrical conductivity values

the temper condition or thermal history can be estimated from this correlation. A linear correlation has been established between the strength and hardness of AA 7010. The UTS can be predicted within a 95% confidence. The 0.2% PS can also be predicted with a similar accuracy from UTS and PS/UTS ratio, which can be estimated from the combination of hardness and electrical conductivity.

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