DETERMINING THE IMPACT TOUGHNESS OF AGE-HARDENED 2024 AL-ALLOY BY NONDESTRUCTIVE MEASUREMENTS

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Abstract: The aim of this study is to investigate the effect of ageing on the impact toughness of 2024 Al-Cu-Mg alloy, and also to search for the ability of sound velocity and electrical conductivity measurements for monitoring of variations in microstructure and impact toughness during ageing. Following the 1 h solutionizing treatment at 493°C and water quench, the specimens were aged at 190°C for various periods (1 to 18 h). The precipitation stages during ageing were monitored by hardness measurements. For each specimen group, Charpy impact and hardness tests were carried out, and sound velocity and electrical conductivity were measured at ambient temperature. During ageing the impact toughness of the alloy first increased, and then, following a maxima decreased due to the precipitation of intermediate phases, finally it reached its minimum at the peak hardness. Correlations between hardness, impact toughness, sound velocity and electrical conductivity were investigated.

Introduction: Age hardened Al-alloys are advantageous for engineering applications due to the considerable improvements in their yield strength and hardness by controlled thermo-mechanical treatments. Micromechanisms governing fracture characteristics of such alloys depend on coherency and distribution of precipitates, grain size and shape, grain boundary precipitates, presence of other second phase particles which result from impurities. The unstable fast fracture, even if it is ductile, becomes frequent because the strengthening lowers the level of toughness, and this becomes a problem with large scale structures. Since the fracture of many engineering components is promoted under dynamic conditions, there is a need to understand the fracture behaviour of materials under dynamic loads. Moreover, fracture characteristics under the impact load seem to become important, because the application to transportation vehicles will increase [1]. Therefore, during fracture mechanics tests, it may be advantageous to include Charpy impact tests so that emprical correlations between the various fracture parameters can be developed.

Various studies have been published on evolution of microstructure, tensile properties and fracture toughness of precipitation hardened Al-alloys [2-11]. Some researchers have also interested in the nondestructive characterization of aged Al-alloys. Hagemaier and Kleint [12] investigated the conductivity-hardness-ageing treatment relationship of Al alloys in various tempers. Gefen *et al.* [13,14] studied the variance in ultrasonic attenuation during ageing of 2024 alloy. Hagemaier [15] established a correlation between conductivity versus strength and hardness versus strength for the 7075-T6 and 2024-T3/T4 alloy specimens. Rosen *et al.* [16] studied the precipitation-hardening in 2219 alloy by measuring sound velocity, attenuation and hardness. Measurements as a function of ageing time at various temperatures were found to exhibit prominent changes and anomalies related to the formation of precipitates. The influence of precipitation kinetics during ageing on electrical conductivity and hardness in both unstretched and plastically deformed 2024 alloy specimens was investigated by Rosen *et al.* [17]. Natan and Chihoski [18] developed a new method of evaluating heat treatments of Al-alloys by constructing in a hardness-conductivity field formed by a network of curved coordinate lines of quenching and ageing times. Rosen *et al.* [19] characterized sound velocity and attenuation, eddy current and hardness measurements on precipitation-hardened 2024 alloy subjected to a series of different pre-ageing heat treatments prior to various tempers. Murav'ev investigated the effect of various types and conditions of heat treatment on the resonance frequency and sound velocity in Al-alloys [20]. However, there is yet little known [1,21] in regard to the effect of precipitation on impact toughness.

Experimental: By machining the rectangular bar of 2024 alloy, fifteen specimen groups, each containing two specimens for hardness, ultrasonic and electrical conductivity measurements and two specimens for impact test were prepared. The specimens were solution treated at 493°C for 1 h, then, quenched into water. They were aged at 190°C for various ageing times (1-18 h). At pre-determined intervals, the specimens were cooled rapidly to room temperature and subjected to the non-destructive measurements and mechanical tests. The aged specimens were kept at -24^{o}C.
The evolution of microstructure was monitored by hardness measurements using a Vickers micro-hardness tester with ± 0,1 accuracy. On each specimen, five hardness values were taken from the different regions to determine a mean value of hardness, and to get information about uniformity. Impact fracture energies were measured with a pendulum type of test machine at room temperature. Fracture surfaces of the Charpy specimens were examined in a scanning electron microscope. The conductivity measurements were performed by means of a Verimet M4900 eddy current system. The system was calibrated on the calibration blocks with known conductivity values. The measured values were considered to be accurate within ±0.5 % International Annealed Copper Standard (IACS). Velocity measurements of ultrasonic longitudinal waves were carried out by using a Panametrics-5052UAX50 analyzer and a Philips-PM3365A oscilloscope with a 20 MHz transducer. The sound velocity was calculated by dividing twice the specimen thickness by the time-of-flight between zero-crossing of two back-wall echoes. Pulse echo technique was used. Oil was applied as a coupling medium at the probe-specimen interface, and a constant force was applied on the probes to obtain a stable thickness of the coupling film. The mean values for the velocities were obtained by averaging the five independent measurements. For achieving the highest possible accuracy, the specimens were carefully machined to have smooth, flat and parallel surfaces. The thickness of specimens was measured with an error of ± 0.001 mm. The time interval between the two subsequent echoes was measured in the microseconds scale.
Results and Discussion: For Al-Cu alloys, the microstructural evolution is complex, and the precipitation sequence varies depending on the degree of super-saturation and the ageing temperature. In the case of 2024 alloy, two successive transitions exist from super-saturated solid solution, namely, GP - θ”- θ’- θ (Al_2Cu) and GPB - S”- S’- S ($CuMgAl_2$). The complete precipitation sequence can only occur when the alloy is aged at temperatures below the GP zone solvus. The mechanism of the transformation sequence usually involves heterogeneous nucleation at the sites of earlier products, resulting in fine and uniform precipitate dispersions [9,27].

The age hardening process is very often investigated by hardness measurements that monitor the precipitation sequence. Fig.1 shows the variation in hardness of 2024 alloy as a function of ageing time at 190°C. Following a remarkable increase from 124 to 154 HV within the first 4 h of ageing, hardness increased slightly up to its maximum (156,7 HV) at 10 h ageing.
The contribution to hardness depends on the coherency of the precipitate with the matrix, size and distribution of the precipitates and the proximity of the particles. In general, the increase in hardness depends on the variation in the stress fields in the vicinity of the precipitate. After quenching from solid solution the alloy contains regions of solute segregation. This clustering produces local strain which results in an increase in hardness. With additional ageing, the hardness is increased further by the ordering of larger clumps of Cu atoms on certain planes of the matrix (θ”). Next, definite precipitate platelets of θ’, which are coherent with the matrix, form. The coherent precipitate produces an increased strain field in the matrix and a further increase in hardness. After longer ageing the equilibrium phase, which is no longer coherent with matrix, is formed. Therefore, the hardness starts to decrease.

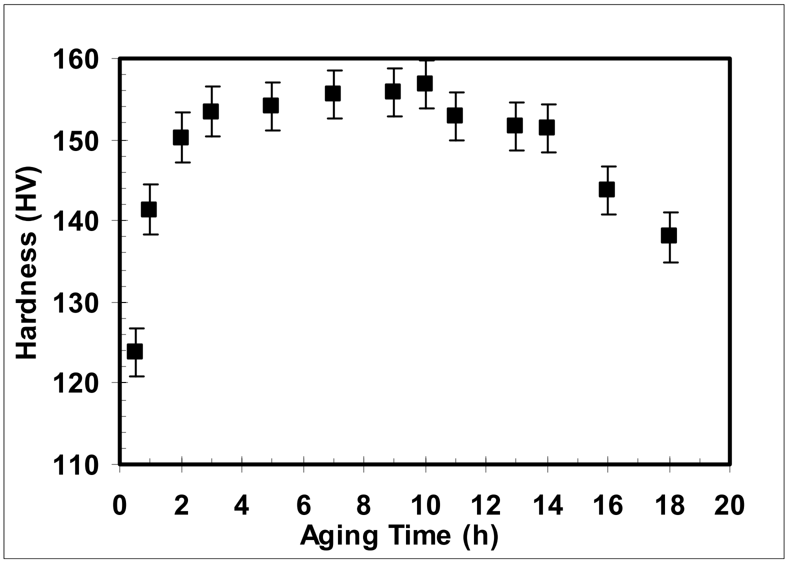


Figure 1. Variation in hardness of 2024 alloy as a function of ageing time at 190°C

The impact toughness is strongly dependent on microstructural variables, and affected by a number of factors, such as yield strength, ductility, temperature, and fracture mechanism. As seen in Fig. 2, the room temperature impact fracture energy of 2024 alloy aged at 190°C reaches its maximum (50 J) within the first five hours, then, decreases down to 15 J at longer ageing times. The specimen with the highest hardness has the lowest impact toughness. The SEM fractographs of the specimens aged for 7 h and 13 h are shown in Fig.3 a) and b). There is a clear difference between the fracture surfaces. Fracture surface associated with the lowest toughness condition has an appearance consisting of dimples; small and shallow voids formed round the larger inclusions. The decrease in impact energy, in contrary to hardness, can be related to the formation of metastable precipitates. Increasing the hardness and the yield strength by precipitation makes the alloy more brittle and decreases the impact fracture energy since less plastic work can be done before the strain in the plastic zone is sufficient to fracture the test specimen. A similar result has been reported for aged 7178 alloy [24]. The results are also in agreement with previous studies on various Al alloys, reporting an increase in strength on ageing is accompanied by a corresponding decrease in the plane-strain fracture toughness [25].

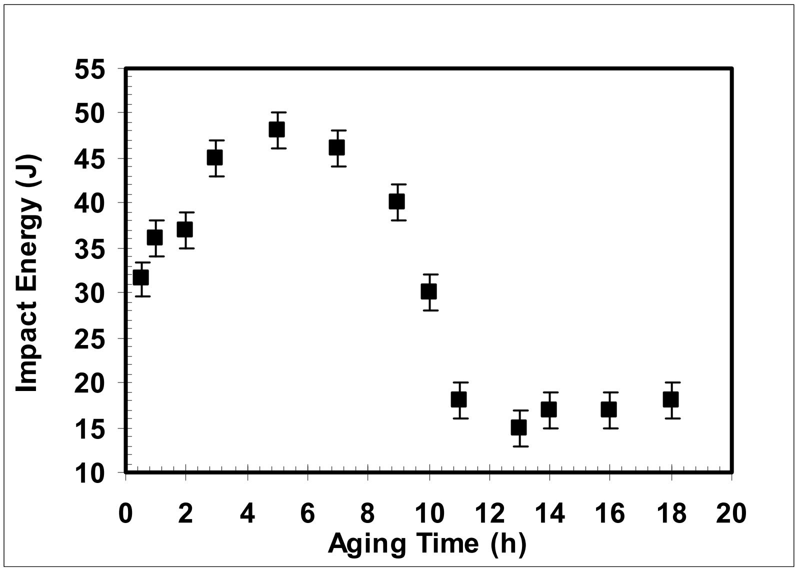
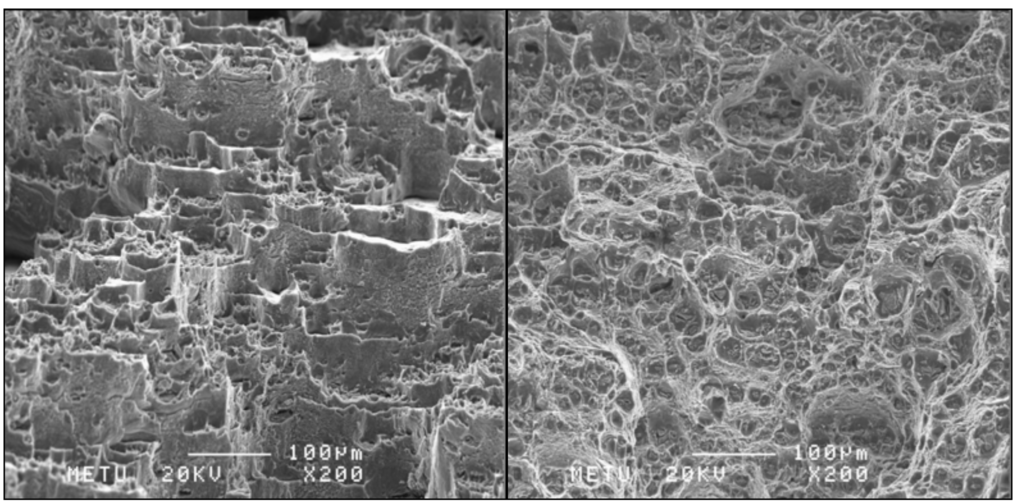


Figure 2. Variation in impact fracture energy of 2024 alloy as a function of ageing time at 190°C



a) b)

Figure 3. Fracture surfaces of impact specimens aged at 190°C a) for 7 h (45 J), b) for 13 h (15 J)

Fig. 4 shows the change of longitudinal wave velocity of the 2024 alloy specimens aged at 190°C for various times. Sound velocity increased with increasing ageing time, and the maxima (6372 m/s) has been reached after 10 h-ageing. This value corresponds to the maximum hardness and minimum impact toughness values. The variation in sound velocity is similar to those reported in the previous studies [16,20]. It has been stated that sound velocity increases as a result of a reduction of the extent of distortions of the crystal lattice due to breakdown of supersaturated solid solution in ageing [20]. The increase in the sound velocity is, then, attributable to the increased volume fraction of precipitates, which contribute to the increased elastic modulus of the aged specimen. During ageing, when coherent zones turn to semi-coherent intermediate precipitates and the volume fraction of precipitates increases, the hardness and the elastic modulus increases so the propagation velocity of wave. The elastic properties of the intermediate precipitates, which are related to the sound velocity, are generally independent of the state of coherency between the precipitate and the matrix.

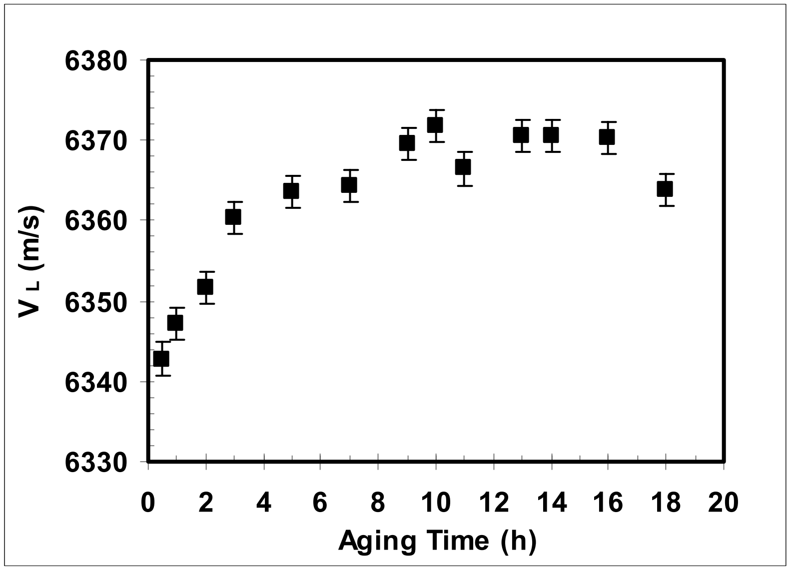


Figure 4. Variation in longitudinal wave velocity of 2024 alloy as a function of ageing time at 190^{o}C

The variation in the electrical conductivity with ageing is complex and results from a number of contributions including changes in the scattering of electrons. Electrical conductivity measurements cannot, in principle, differentiate between GP zones since changes in conductivity are determined more by the number and size of the scattering centers than by their crystal structure or degree of coherency with Al-matrix. Fig. 5 shows that electrical conductivity of 2024 alloy increases from 31 to 41,3 % IACS with increasing ageing time. These values are in agreement with previous results [15-17]. The reason of the increase in electrical conductivity is thought to be the purification of the matrix by means of segregation of the solute atoms and formation of semi-coherent metastable phase. As the rate of precipitation is accelerated, the foreign atoms that act as scattering centers of electrons segregate from the aluminium matrix at an enhanced rate. Equilibrium precipitates are larger particles and increase in size as ageing proceeds, thus minimizing their scattering effect. In the under-aged to peak aged region, the impact toughness is inversely proportional to the electrical conductivity.

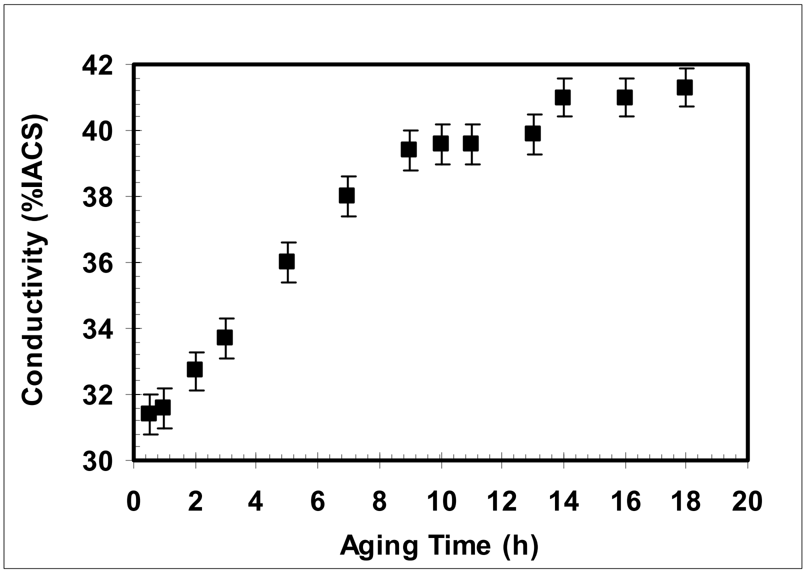


Figure 5. Variation in electrical conductivity of 2024 alloy as a function of ageing time at 190°C

Conclusions: After solutionizing at 493°C for 1 h and quenching, the variance in the impact toughness, sound velocity, and electrical conductivity of 2024 Al-alloy as a function of ageing time at 190°C was determined. The stages of precipitation process were monitored by the hardness measurements.

Sound velocity increased with increasing ageing time, and the maximum value has been reached after 10 h-ageing. This value corresponds to the maximum hardness. This is attributable to the increased volume fraction of precipitates, which contribute to the increased elastic modulus of the aged specimen. During ageing, when coherent zones turn to semi-coherent intermediate precipitates and the volume fraction of precipitates increases, the hardness and the elastic modulus increases so the propagation velocity of wave.

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Impact fracture energy makes a maximum within the first five hours, then, decreases to 15 J at longer ageing times. The decrease in impact energy, in contrary to hardness, can be related to the formation of metastable precipitates. Increasing the hardness and the yield strength by precipitation makes the alloy more brittle and decreases the impact toughness since less plastic work can be done before the strain in the plastic zone is sufficient to fracture the test specimen. The specimen with the lowest impact toughness corresponds to the highest values of hardness and sound velocity, and a high value of electrical conductivity.

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