

Empirical Correlation of Strength With Hardness and Electrical Conductivity For Aluminium Alloy EN AW-7075 T4

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The aim of this work was to establish an empirical correlation between strength, hardness and electrical conductivity, i.e. mechanical and physical properties of the EN AW-7075 alloy during the natural ageing.

The results indicate a good correlation between hardness/strength and electrical conductivity. It was found that the correlation between 0.2% proof strength ($R_{p0.2}$) and tensile strength (R_m) with hardness (HB) and electrical conductivity, as well as hardness with electrical conductivity, exhibit a nonlinear dependence, with the coefficient of determination, R^2 , between 0.9618 and 1. These relationships can be used for monitoring the ageing and predict the strength by nondestructive testing.

Key words: EN AW-7075 T4, 0.2% proof strength ($R_{p0.2}$), tensile strength (R_m), hardness, electrical conductivity, coefficient of determination R^2 .

Introduction

ALUMINUM alloys of the precipitation-hardening Al-Zn-Mg-Cu system (7xxx) exhibit the highest strength of all aluminum alloys. The EN AW-7075 alloy is one of the most common aluminum alloy used in aircraft, aerospace technology, vehicles, buildings and other constructions, due to superior high strength/weight ratio, good fatigue strength and fracture toughness, and average machinability. Their strength is achieved through a combination of heat treatment processes, including solution heat treatment, quenching, and age hardening. During this process, dissolution of soluble phases, supersaturation, and precipitation occur. Age hardening process can be performed either at the room temperature (natural ageing) or at an elevated temperature (artificial ageing).

Electrical conductivity measurement is widely used for characterization of nonferrous metals and alloys, since it is sensitive on microstructural changes that affect strengthening mechanisms: solid solution strengthening, grain boundary strengthening, strain hardening and second phase strengthening or precipitation strengthening. Electrical conductivity is also sensitive on temperature and residual stress [1-3]. All enumerated strengthening mechanisms reduce the electrical conductivity by scattering conduction electrons from their path [4-6]. Among many available nondestructive techniques, electrical conductivity measurement is a quick and one of the most preferred and widely used for monitoring

and verification of the heat treatment of age hardenable aluminum alloys [7-8].

Although the full-strength capability of an alloy is not reached by natural ageing, the alloys of 7xxx are used in T3 and T4 tempers, whereas the mechanical properties are stable and adequate for many applications. In most cases naturally aged condition is used as a step prior artificial ageing or forming operations and artificial ageing [9-10]. It was shown that natural ageing affects the subsequent artificial ageing behavior and improves strength and ductility of AlZnMgCu alloys [11-12]. Fine GP zones are homogeneously formed during natural ageing, which additionally suppress the grain boundary (GB) precipitation [11]. The precipitation of supersaturated solid solution after solution heat treated and quenching, occurred after some incubation period [4, 10, 13-14].

During natural ageing the multistage precipitation (SSSS-GP-metastable η' -stable η phase) characteristic of artificial ageing is absent. The only precipitates to form are the Guinier-Preston (GP) zones. The major contribution to hardening occurs at the beginning of the ageing and the hardness and strength increase due to homogenous precipitation of coherent GP zones (Zn/Mg) [7, 15-17]. The precipitation is followed by a change of physical properties (electrical and thermal conductivity).

Understanding the relationship between the physical and mechanical properties of high-strength aluminum alloys of the 7xxx series would be beneficial for a nondestructive

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evaluation of the microstructure after heat treatment. This correlation offers a practical method for estimating strength from electrical conductivity measurements. Regression analysis is a standard statistical method for establishing empirical relationships between experimentally measured quantities. Linear regression determines the coefficients of a polynomial function by minimizing the least squares error, with the coefficient of determination (R^2) and adjusted R^2 quantifying the goodness of fit to experimental data.

The aim of this work is to suggest an empirical relationship between strength, hardness, and electrical conductivity that could be used to nondestructively estimate the strength/hardness of the EN AW-7075 -T4 alloy.

Materials and methods

Chemical composition of the commercial EN AW-7075 aluminum alloy received as extruded billets 90 mm in diameter, tested in this work is given in Table 1.

Table 1. Chemical composition of tested EN AW-7075 alloy (wt. %)

Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr	Zr	Al
1.51	2.88	0.06	0.11	0.25	6,0	0.07	0.15	0.1	Bal.

Heat treatment of the alloy consisted of solution treating at 485°C for 45 minutes, followed by a rapid quenching in water, and finally natural age hardening.

The mechanical properties and electrical conductivity were evaluated after 2, 4, 24, 48, 72, 144, 168, 192, 216, 240 and 360 hours of natural age hardening.

Hardness was measured by the Brinell method according to SRPS EN-6506-1 [18]. Tensile test was performed on the Instron 8032 testing machine, according to SRPS EN 10002-1 standard [19], using round cross-section specimens of 6 mm in diameter and 30 mm in gauge length. Electrical conductivity measurements were performed using Förster SIGMATEST D 2.068.

Results and discussion

Figure 1 shows nominal tensile stress–strain curves of the AAEN AW-7075 alloy in water quenched (WQ) and naturally aged for 240 h condition (T4 temper). Strain hardening behavior of these tempers is similar and both curves exhibit serrated yielding in the stress–strain curve due to Portevin Le Chatelier effect, which is typically observed in these alloys [20–22]. However, the effect of natural ageing on the tensile properties is clear – the results exhibit marked increase of 0.2% proof strength ($R_{p0.2}$) and tensile strength (R_m), along with a decrease in the elongation in T4 temper.

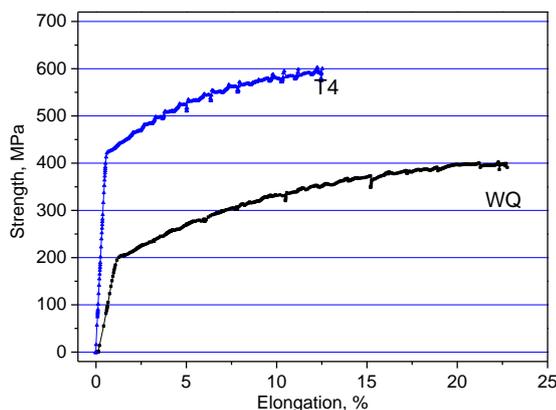


Figure 1. Stress-strain curves of EN AW-7075 alloy samples, water quenched (WQ) and naturally aged for 240 hours (T4).

The influence of natural ageing time on mechanical properties, 0.2% proof strength ($R_{p0.2}$) and tensile strength (R_m), and hardness is shown in Figures 2 and 3. Strength and hardness increase for all ageing times. The most pronounced increase of the strength and hardness was registered in the beginning of the natural ageing, i.e. up to 48 hours of ageing. The strength of water quenched alloy increased from about 200 MPa, to almost 430 MPa ($R_{p0.2}$) and 600 MPa (R_m) after natural ageing.

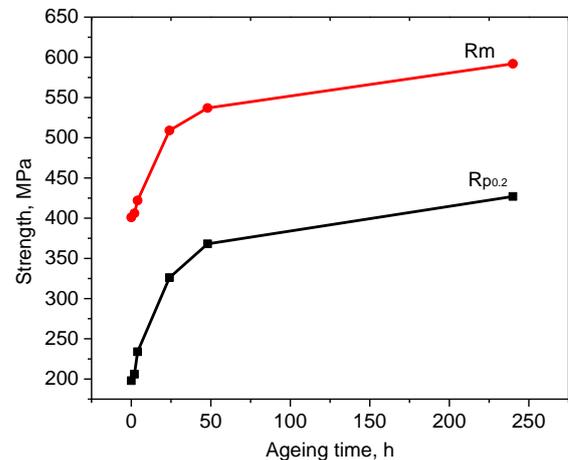


Figure 2. Influence of ageing time on strength.

Figure 3 shows the hardness change of water quenched samples with the duration of natural ageing up to 360 hours. The hardness increased from 84 HB in water quenched state up to 127 HB after natural ageing. The rapid increase of the hardness was also observed after up to 48 hours. The results indicate that plateau of the hardness-ageing time curve was reached after 72 hours, while maximal hardness was reached after 144 ageing hours (6 days).

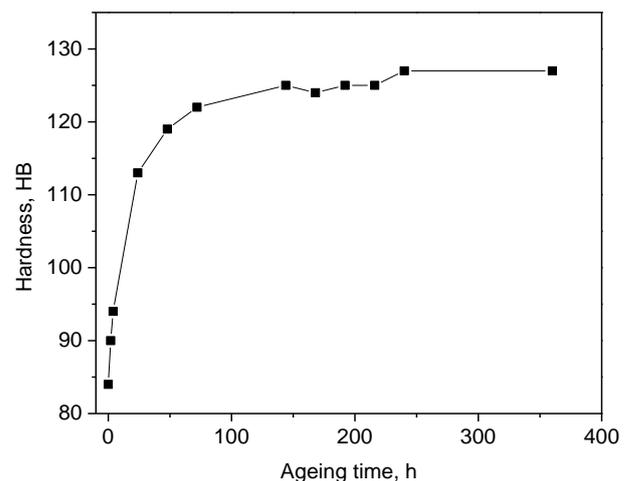


Figure 3. Influence of ageing time on hardness.

Natural ageing occurs when a supersaturated alloy begins to age by the formation of GP zones [13]. The GP zones form at a high rate due to high diffusion coefficient and the high concentration of vacancies [14, 23]. Therefore, the first part of the curve exhibits a high slope, indicating intensive formation of the GP zones. These very fine zones, with no distinct boundary to the surrounding matrix, obstruct the motion of the dislocations, causing the intensive strengthening. The strain field around coherent GP zone, induced by a mismatch

between Al matrix and these zones, enhances the resistance to dislocation motion and thus strengthens the alloy. As the number of the zones increase, the hardness/strength increases. The hardness curve has reached the plateau after approximately 10 days, although the properties of aluminum alloys in natural ageing condition are less stable compared to artificial ageing, and exhibit changes after many years [4].

During the natural ageing electrical conductivity decreases with time (Figure 4). With the increase of hardness/strength, the electrical conductivity of the alloy decreases. In the same period of time when hardness/strength rapidly increases (Figures 2 and 3), electrical conductivity rapidly decreases (steeply fall). Continued ageing leads to a further decrease of electrical conductivity.

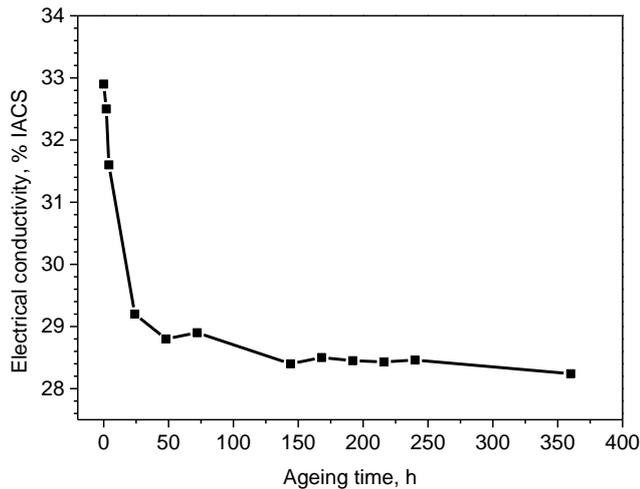


Figure 4. Influence of ageing time on electrical conductivity.

Decrease of electrical conductivity also indicates the

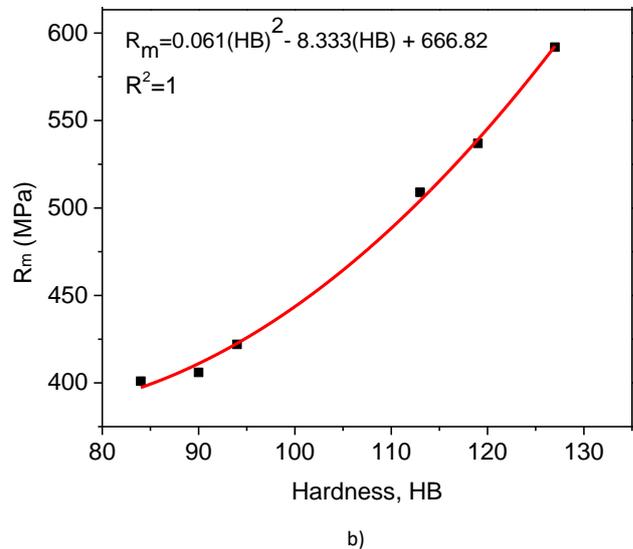
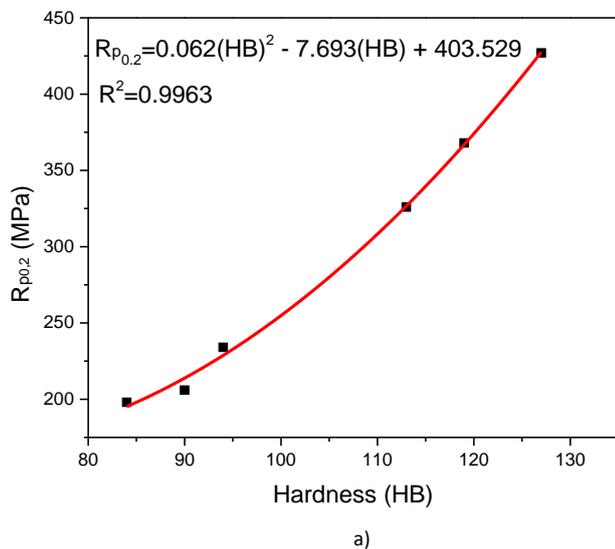


Figure 5. Strength-hardness relationship after natural ageing: a) 0.2% proof strength ($R_{p0.2}$) and b) tensile strength (R_m)

Figure 6 shows 0.2% proof strength and tensile strength relationship with electrical conductivity.

formation of GP zone. During the initial stages of precipitation, the formation of the GP zones plays a dominant role. Even though the concentration of solute atoms from solid solution slightly reduces due to the migration of the solute atoms to the GP zones, which leads to an increase of electrical conductivity, the electrical conductivity decreases. Obviously, the solute clusters strongly scatter the electrons from their path, and this contribution to the electrical conductivity is higher, so the resulting electrical conductivity decreases [1, 3].

Figure 5 shows the relationship between 0.2% proof stress and tensile strength ($R_{p0.2}$, R_m) and the hardness for the naturally aged samples. Both figures imply nonlinear relationships.

Relationship 0.2% proof strength - hardness is given by:

$$R_{p0.2} = 0.062(\text{HB})^2 - 7.693(\text{HB}) + 403.529, R^2 = 0.9963 \quad (1)$$

while relationship tensile strength, R_m - hardness is given by:

$$R_m = 0.061(\text{HB})^2 - 8.333(\text{HB}) + 666.82, R^2 = 1 \quad (2)$$

Determination coefficient (R^2) has a value between 0 and 1. Values closer to 1 indicate that the model fits the data better. Although, R^2 coefficient is not standard for evaluating model fit in regression analysis, and is not recommended in complex cases and some report as "pseudo R^2 ", most statistical software calculate R^2 for nonlinear models [24-26]. Also, there are some opinions that R^2 can be useful as a reality check for evaluating repeated experiments and it is still frequently used within scientific literature for the analysis and interpretation of regression analysis [27]. In present case, the dependence between strength, hardness and electrical conductivity is described by a quadratic polynomial.

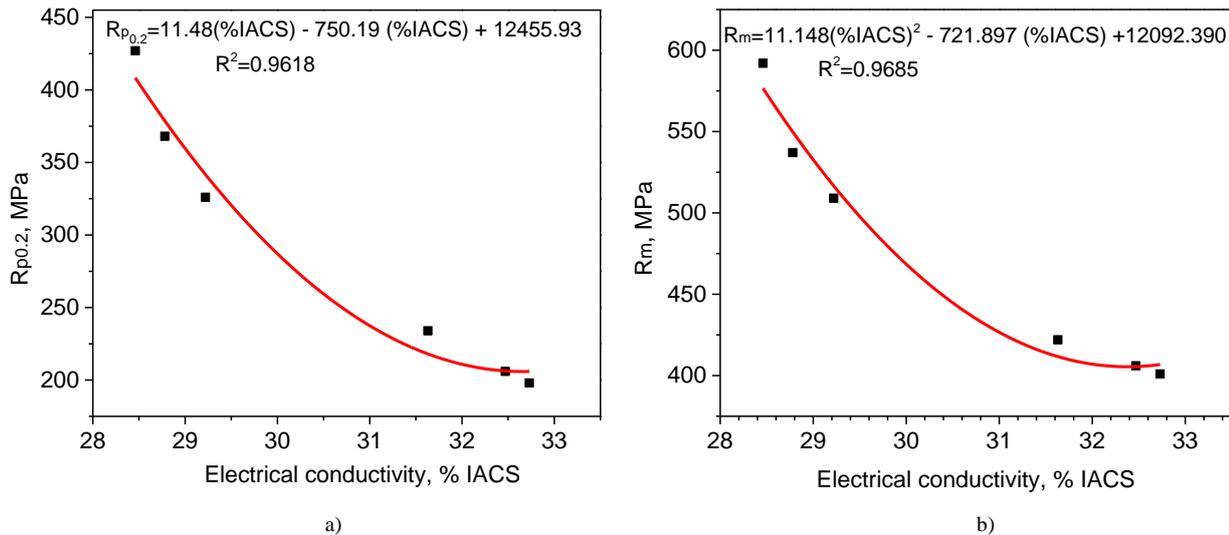


Figure 6. Strength-electrical conductivity relationship after natural ageing: a) 0.2 proof strength ($R_{p0.2}$) and b) tensile strength (R_m)

Relationships between ($R_{p0.2}$) and (R_m) with electrical conductivity are described by equations (3) and (4):

$$R_{p0.2} = 11.48 (\%IACS)^2 - 750.19 (\%IACS) + 12455.93 \quad (3)$$

$$R_m = 11.148(\%IACS)^2 - 721.897 (\%IACS) + 12092.390 \quad (4)$$

Coefficient of determination, R^2 , for equations (3) and (4) has high values of $R^2=0.9618$ and $R^2=0.9685$, respectively.

In Figure 7 the hardness values versus electrical conductivity were plotted. The coefficient of determination (R^2) of the equation (5) exhibits a quite high value of $R^2=0.98293$. In this case linear fitting exhibits slightly lower values $R^2=0.98067$, and thus it can also be used with a good accuracy.

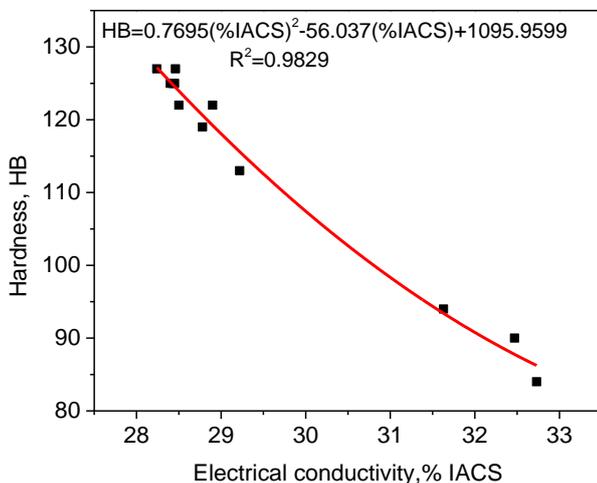


Figure 7. Brinell hardness - electrical conductivity relationship after natural ageing.

$$HB = 0.7695 (\%IACS)^2 - 56.037(\%IACS) + 1095.9599, R^2 = 0.9829 \quad (5)$$

Since numerical approach has no physical meaning, in this paper only the equations with the best fit are presented. The excellent nonlinear relationship between strength ($R_{p0.2}$ as well as R_m) or hardness, and electrical conductivity with the high coefficient of determination ($R^2=0.9963$ and $R^2=1$, respectively), implicates that the prediction of strength based on the hardness value can be used with a reasonable degree of accuracy.

Prediction of strength based on electrical conductivity measurement was also possible with a high accuracy. The coefficients of determination were $R^2=0.9618$, and $R^2=0.9685$, for $R_{p0.2}$, as well as R_m , respectively.

Similar relationship between strength/hardness and electrical conductivity for naturally aged 7xxx alloy was reported by MA Salazar-Guapuriche and explained as a result of the differences in response of electrical conductivity and hardness with age hardening [28].

Although some authors published linear dependence between strength/hardness with electrical conductivity of age hardening aluminum alloys (Salazar-Guapuriche, MA, [28-31]), in this work the excellent nonlinear dependence was found. In this case, the quadratic model demonstrates a nonlinear dependence of alloy strength and hardness on electrical conductivity, with higher adjusted R^2 than the linear fit.

These results show that electrical conductivity is a practical tool to monitor natural ageing in time and with, or even without hardness measurement, given empirical equations can have a practical application for estimation strength of AAEN AW-7075 alloys with reasonable accuracy.

Conclusion

The results show that natural ageing enhances the strength of EN AW-7075 aluminum alloy. The nonlinear relationship was established between the strength and both the hardness and the electrical conductivity.

It was found that the relationship of $R_{p0.2}$ and R_m with the hardness (HB) can be described by a quadratic function with R-squared values of 0.9963 and 1, respectively. Similar dependence of $R_{p0.2}$ and R_m with the electrical conductivity was established, with R-squared values of 0.9618 and 0.9685, respectively, as well as for the hardness and electrical conductivity, with R-squared value of 0.9829.

These empirical correlations can be used for monitoring precipitation during ageing and predict the strength by nondestructive testing.

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Korelacija čvrstoće i tvrdoće i električne provodljivosti legure EN AW-7075 T4

Cilj rada je bio da se uspostavi korelacija između eksperimentano dobijenih vrednosti čvrstoće, tvrdoće i električne provodljivosti legure EN AW-7075 T4. Rezultati su pokazali odličnu korelaciju tvrdoće/čvrstoće i električne provodljivosti. Utvrđena je nelinearna zavisnost granice popuštanja ($R_{p0.2}$) i zatezne čvrstoće (R_m) od tvrdoće (HB) i električne provodljivosti, sa koeficijentom determinacije R^2 od 0,9618 do 1. Ove zavisnosti mogu biti korišćene za praćenja procesa starenja i procene čvrstoće legure primenom metoda bez razaranja.

Ključne reči: EN AW-7075 T4, granica popuštanja ($R_{p0.2}$), zatezna čvrstoća (R_m), tvrdoća, električna provodljivost, koeficijent determinacije R^2 .