IIAC 2014

25 - 26 May, 2014, Tehran, Olympic Hotel

IU ST
Iran University of Science & Technology

مرکز تحقیقات آلومینیوم ایران
Iran Aluminium Research Centre

IMI DRO
Iranian Mines and Mineral Industries
Development and Renovation Organization

ABSTRACT BOOK
Iran International Aluminium Conference

Chairman:
Prof. M. Soltanieh

Scientific Chairman:
Prof. M. Aboutalebi

IIAC 2014

ALUMINIUM KEY TO A SUSTAINABLE INDUSTRY

Quality Control of Precipitation Hardened Aluminium Alloy Parts via Eddy-current Non-destructive Evaluation

Ali Abbasian, Mehrdad Kashefi, Esmaeel Ahmadzade Beyraki

Department of Materials Engineering & Metallurgy, Ferdowsi University of Mashhad, Mashhad, P.O. Box: 91775-1111, Iran

Abstract:

Precipitation hardening is the most common method in the strengthening of aluminium alloys. This method relies on the decrease of solid solubility with temperature reduction to produce fine precipitations which impede the movement of dislocations. The quality control of aluminium alloy specimens is an important concern for engineers. Among different methods, non-destructive techniques are faster, cheaper and are able to be used for 100% of specimens. To assess the ability of eddy current as a non-destructive method in the evaluation of precipitation hardening of aluminium alloys, 7075 aluminium alloy specimens were solution treated at 480°C for 1 hr, followed by water quenching. Afterwards, the specimens were aged at different temperatures of 200, 170, 140, 110 and 80°C for 8 hr. Eddy current measurements was conducted on the aged specimens. Hardness measurement and tensile test were employed to investigate the mechanical properties. It was demonstrated that eddy current is effectively able to separate the specimens with different aging degree due to the change of electrical conductivity during aging process.

Keywords: 7075 aluminium alloy, precipitation hardening, Eddy current, Non-Destructive evaluation.

Quality Control of Precipitation Hardened Aluminium Alloy Parts via Eddy-current Nondestructive Evaluation

Ali Abbasian, Mehrdad Kashefi, Esmaeel Ahmadzade Beyraki

Department of Materials Engineering & Metallurgy, Ferdowsi University of Mashhad, Mashhad, P.O. Box: 91775-1111, Iran

Abstract: Precipitation hardening is the most common method in the strengthening of aluminium alloys. This method relies on the decrease of solid solubility with temperature reduction to produce fine precipitations which impede the movement of dislocations. Quality control of aluminium alloy specimens is an important concern of engineers. Among different methods, non-destructive techniques are faster, cheaper and are able to be used for 100% of specimens. To assess the ability of eddy current as a non-destructive method in evaluation of precipitation hardening of aluminium alloys, 7075 aluminium alloy specimens were solution treated at $480^{\circ}C$ for 1 hr and followed by water quenching. Afterwards, the specimens were aged at different temperatures of 200, 170, 140, 110 and $80^{\circ}C$ for 8 hr. eddy current measurements was conducted on the aged specimens. Hardness measurement and tensile test were used to investigate the mechanical properties. It was illustrated which eddy current is effectively able to separate the specimens with different aging degrees due to the changes in electrical conductivity during aging process.

Keywords: 7075 aluminium alloy, precipitation hardening, Eddy current, Non-Destructive evaluation.

Introduction

Eddy current non destructive evaluation is based on the induction of current in a conductive material which is placed in an alternative magnetic field (farady's law). The induced current (eddy current) generates a magnetic field (amper's law) which contracts with the primary magnetic field to reduce it (len's law). In eddy current testing, primary magnetic field is provided by a coil which is fed by an alternative current. A Secondary coil is also used to pick up the changes of magnetic field caused by presence of conductive material in primary field vicinity.

Eddy current depends on the frequency and material electromagnetic properties. Usually in eddy current testing magnetic field parameters are constant and only the material properties changes the eddy current outputs. magnetic permeability and electrical conductivity are two main properties which affect eddy current response, however, harmonic analysis, as an eddy current output used for ferromagnetic materials, depends on the shape of magnetic hysteresis loop[1]. Variation of chemical composition, microstructure, stress and strain in conductive materials affect electromagnetic properties. Many investigations prove the applicability of this method in determination of microstructure and mechanical properties of metals. W. Yin et al used eddy current technique in Measurement of electromagnetic properties of power station steels [2]. Permeability and ferrite/austenite fraction were measured by multi frequency eddy current technique [3]. It was demonstrated in which low frequency range eddy current output depends mostly on magnetic permeability and by increasing the frequency electrical conductivity dependence is increased due to the increase of induced current in samples[2-6].

In Authors' researches carburizing and decarburizing depth of steel were determined by eddy current [7-8]. Tempered martensite embritlment and hardness profile of induction hardened steel parts were also ascertained by this method [9-10]. Effect of elastic stress in different aluminum alloys on pulsed eddy current output was studied by M.morozov et.al [11].

During aging, by heating the super saturated aluminum alloy, the excess solute elements leave their highly stressed places to produce stable fine particles of an impurity phases. These particles harden the material by obstructing the motion of dislocations. In addition, this process affects the electrical conductivity by two competitive mechanisms, first the purifying of matrix from alloying atoms, and the decrease of quenched vacancies which increase the electrical conductivity and second the scattering of conduction electrons with precipitations which reduces the conductivity. Therefore, according to the importance of heat treatment controlling of this alloy and the ability of eddy current method in monitoring of electrical conductivity variations, the ability of this nde technique was investigated in controlling of aging process of 7075 al-alloy.

Experimental Procedure

7075 aluminium alloy with chemical composition summarized in **Table 1** was used in this study. Before heat treatment, 3 tensile samples according to ASTM–B557 and also a cylindrical sample with 16mm in diameter and 20cm in length were prepared for each degree of aging. These samples were solution treated at $480^{\circ}c$ for an hour then followed by water quenching. Different degrees of aging were carried out on samples by heating at temperatures of 200, 170, 140, 110 and $80^{\circ}C$ for 8 hr. discs with 2 cm length were cut from end of cylindrical samples for hardness measurement. Tensile testing was carried out on the specimens at room

temperature and strain rate of $0.002s^{-1}$. Eddy current testing was applied on the samples at the optimum frequency of 6KHz in which the eddy current response has the maximum resolution in the separation of samples with different aging temperatures. Schematic of eddy current measurement is illustrated in **Figure 1**. This system consists of a function generator to apply sinusoidal current to a coil (with 1900 turns,150mm length and 16mm in diameter) and an A/D card to convert the probe voltages to digital data and interface with personal computer. Impedance output was calculated by dividing the coil voltage to current (equation 1), and impedance phase angel was measured from equation 2, then according to equation 3, real and imaginary impedance were calculated.

Table 1: Chemical composition of 7075 Al-alloy.

Element	Al	Cu	Mn	Mg	Zn
Wt%	Bal.	1.25	0.25	2.305	5.2
Element	Ti	Cr	Si	Fe	Pb
Wt%	0.18	0.25	0.38	0.45	0.45

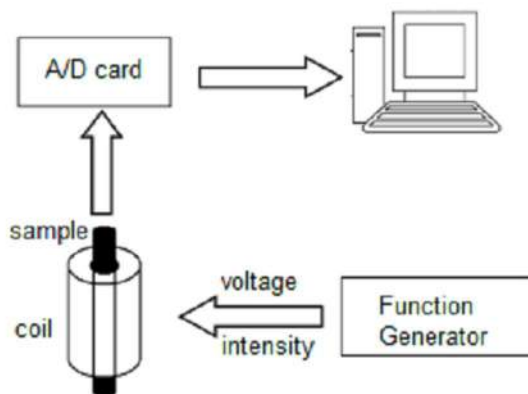Figure 1: Schematic of eddy current evaluation.

$$|Z| = |\frac{V}{I}| = \sqrt[2]{X^2 + R^2} \qquad (1)$$

$$\Phi = 360(\frac{\Delta t}{T}) \qquad (2)$$

$$|X| = |Z| \sin\varphi, \; |R| = |Z| \cos\varphi \qquad (3)$$

In these equations, Z, V, I, X, R, φ, Δt and T are respectively Impedance value, Voltage, electrical current, induction resistance, real resistance, phase angle, the time difference between two adjacent peaks of voltage and current waves and T is wave length.

Results and Discussions

Mechanical properties

Variations of mechanical properties are tabulated in **Table 2**. Different aging degrees were produced by employing various heating temperatures in constant 8hr duration. Hardness, ultimate tensile and yield strength are increased with increasing temperature until 140°C, while their total elongation are decreased, then, their variation are reversed in further temperatures. The sequences of precipitation hardening can be explained by the following:

Solid solution $\rightarrow$ GP Zones $\rightarrow$ GP$_{II}$ Zones $\rightarrow$ $\eta^{'}$ $\rightarrow$ η

An increase in the temperature of super saturated solid solution leads in formation of small dispersed GP Zones with coherent interface with matrix. Until the precipitates are small and coherent they can be cut by dislocations. in further temperatures or aging times, precipitates growth and GP$_{II}$ Zones and then $\eta^{'}$ formed. GP$_{II}$s are bigger and increase the strength of samples by orowan mechanism. $\eta^{'}$ with its semi-coherent also strengthening the alloy due to the non-coherent strain of this phase. Over aging will increases the distance between the precipitates and also produces η particles with non-coherent interface which both of these, reduce the hardness of specimens[12-13]. In fact, the maximum harness will be obtained when the precipitates are mostly GP$_{II}$ and with significant amount of $\eta^{'}$ particles [14]. Therefore, it seems that in 140°C, the presence of these two particles provides the maximum strength in the samples.

Table 2: mechanical properties variation with aging temperature.

Aging Temperature(°C)	80	110	140	170	200
Hardness(Vickers)	132	155	190	160	124
0.2% offset yield strength(MPa)	336	365	580	370	298
Ultimate Strength(MPa)	403	481	591	461	357
Elongation%	11.45	10.49	6.57	8.4	12.9

Eddy current Study

Eddy current responses are affected by electrical conductivity variations of specimens. **Figure 2** shows the position of impedance points of different aging temperatures in impedance plane.

Impedance plane can be described by two parameters, impedance value and phase angle. Variations of these two parameters with aging temperatures are illustrated in **Figure 3**. As aging temperature is increased, these two outputs are decreased. As it was mentioned before, during aging, purification of alloy matrix increases the electrical

conductivity which causes in much eddy current in samples. In contrast, formation of small particles which scatter the conduction electrons, reduce the conductivity. Hence, it can be say, the decrease in eddy current outputs are refers to domination of the effect of purification in the increase of electrical conductivity. It should be reminded that increase of induced current in samples, due to the increase of conductivity, will generates much magnetic field which is opposing with primary field and reduces the magnetic flux density. Therefore, an increase in conductivity results in reduction of induction resistance (X_L) and real resistance(R). thus, according to equation 1, the increase of conductivity in samples due to the aging process, decreases the impedance value.
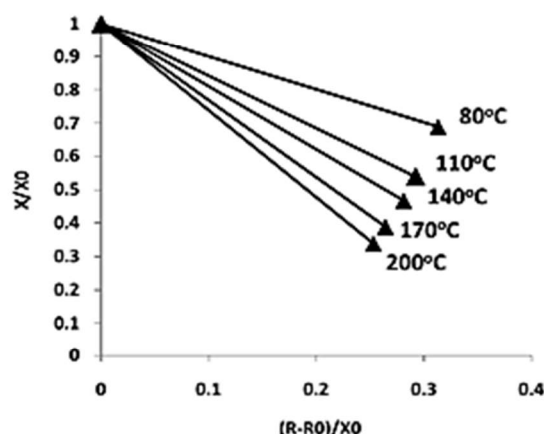

Figure 2: Impedance plane and effect of aging temperature on location of impedance point.
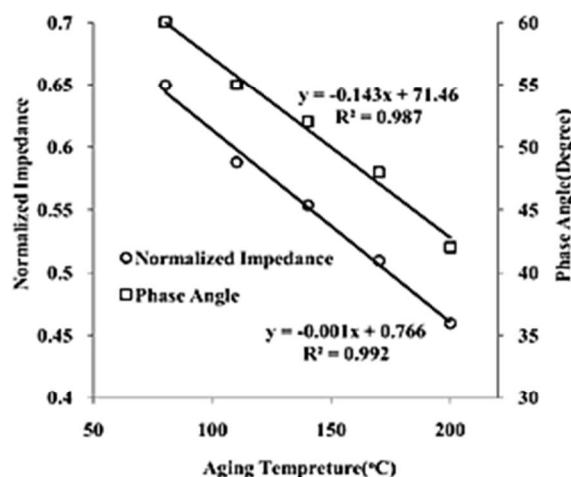

Figure 3: Variation of Normalized Impedance and Phase angle with Aging temperature.

Controlling the aging process in order to achieve the maximum strength is an important issue in the heat treatment of industrial parts. **Figure 4** illustrates the relationship of mechanical properties with eddy current response. This figure also depicts the quality control range defined for variation of impedance values in which acceptable strength or hardness can be obtained. In the variation range of 0.53 to 0.57 of normalized impedanc variation of hardness, yield and ultimate strength are in range of 175 to 190 vickers, 480 to 580 and 530 to 591MPa, respectively. which means, in this impedance range, eddy current technique can automatically separates parts with maximum mechanical properties from unaccepted ones.
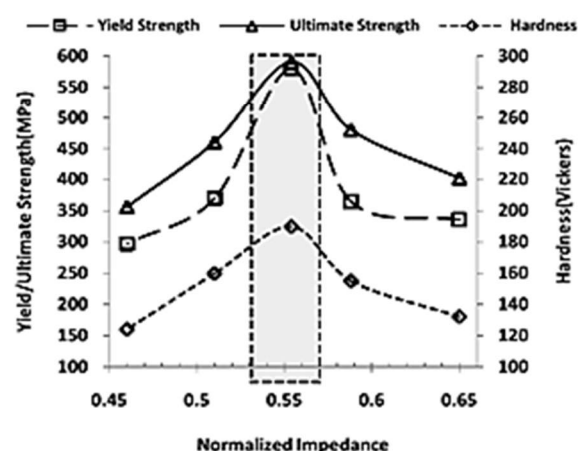

Figure 4: Relationship between the mechanical properties and normalized impedance.

Conclusion

In this study, applicability of eddy current non-destructive method was investigated in the evaluation of aging process of 7075 Al-alloy. This technique was capable in assessment of different degrees of aging due to their difference in electrical conductivity. Good resolution in determination of mechanical properties provides to define a controlling range of impedance in order to obtain parts with maximum hardness, yield and ultimate strength.

References

[1] H. Klümper-Westkamp,H.-W. Zoch,W. Reimche and F. Bach, "High Temperature Resistant Eddy Current Sensor for "in situ" Monitoring the Material Microstructure Development of Steel Alloys during Heat Treatment–Bainite Sensor", *Procedia Engineering*. 25(2011) 1605-1608.

[2] W. Yin, N. Karimian, J. Liu, X. Hao, L. Zhou, A. Peyton, et al., "Measurement of electromagnetic properties of power station steels", *NDT & E International*. 51(2012) 135-141.

[3] R. Haldane,W. Yin,M. Strangwood,A. Peyton and C. Davis, "Multi-frequency electromagnetic sensor

measurement of ferrite/austenite phase fraction—Experiment and theory", *Scripta materialia*. 54(2006) 1761-1765.

[4] X. Hao,W. Yin,M. Strangwood,A. Peyton,P. Morris and C. Davis, "Off-line measurement of decarburization of steels using a multifrequency electromagnetic sensor", *Scripta materialia*. 58(2008) 1033-1036.

[5] N. Karimian,J. Wilson,A. Peyton,W. Yin,J. Liu and C. Davis, "Differential permeability behaviour of P9 and T22 power station Steels", *Journal of Magnetism and Magnetic Materials*. 352(2014) 81-90.

[6] J. Liu,X. Hao,L. Zhou,M. Strangwood,C. Davis and A. Peyton, "Measurement of microstructure changes in 9Cr–1Mo and 2.25 Cr–1Mo steels using an electromagnetic sensor", *Scripta materialia*. 66(2012) 367-370.

[7] S. Kahrobaee,M. Kashefi and A. Saheb Alam, "Magnetic NDT Technology for characterization of decarburizing depth", *Surface and Coatings Technology*. 205(2011) 4083-4088.

[8] M. Sheikh Amiri and M. Kashefi, "Application of eddy current nondestructive method for determination of surface carbon content in carburized steels", *NDT & E International*. 42(2009) 618-621.

[9] S. Kahrobaee and M. Kashefi, "Hardness profile plotting using multi-frequency multi-output electromagnetic sensor", *NDT & E International*. 44(2011) 335-338.

[10] M. Kashefi,A. Rafsanjani,S. Kahrobaee and M. Alaee, "Magnetic nondestructive technology for detection of tempered martensite embrittlement", *Journal of Magnetism and Magnetic Materials*. 324(2012) 4090-4093.

[11] M. Morozov,G. Yun Tian and P.J. Withers, "The pulsed eddy current response to applied loading of various aluminium alloys", *NDT & E International*. 43(2010) 493-500.

[12] G. Koch and D. Kolijn, "The heat treatment of the commercial aluminum alloy 7075", *Journal of Heat Treating*. 1(1979) 3-14.

[13] M.A. Salazar-Guapuriche,Y. Zhao,A. Pitman and A. Greene. "Correlation of strength with hardness and electrical conductivity for aluminium alloy 7010". in *Materials science forum*. 519 (2006)853-858.

[14] R.A. Hall, "Sensor development for intelligent processing of age hardenable aluminum alloys", Ph.D. Thesis, Naval Postgraduate School ,Monterey, California., 1995.