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Investigation on Quench Sensitivity Characterization of Selected Heat-treatable Al Alloys based on Jominy End Quench

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In this paper, a demonstration quench testing system of Jominy End Quench method apply to heat treatable aluminum alloys has been established. The quench sensitivity of some selected 2000 and 7000 series Al alloys has been determined by using this methodology. The results indicated that quench sensitivity and therefore the mechanical properties inhomogeneity in large plates or forgings can be predicted more accurately by the simultaneous combination of hardness and electrical conductivity measurements based on Jominy end quench. The Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr and AA2D70 alloy exhibited the least quench sensitivity, but the AA7B04, AA7050 and AA2124 alloy were affected by cooling rate, and the AA7B04 was the most quench sensitive. If the 90% of the maximum hardness is defined as the depth of quenching, the depth of AA7B04, AA7050 and AA2124 Al alloy through Jominy end quenching is about 20, 55 and 55 mm respectively. Meanwhile, the depth of greater than 150 mm is achievable in the Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr and AA2D70 alloy, and hence it can be recommended to fabricate large section plates or forgings without compromising properties in the center of the part after a slow cool.

Keywords: *Heat treatable Al alloys; Quench sensitivity; Jominy End Quench; Electrical conductivity*

1. Introduction

High strength 2000 and 7000 series Al alloys are widely used for structural applications in aerospace because of their specific mechanical properties, and both 7000 and 2000 series Al alloys are precipitation or age-hardenable [1-5]. Both 7000 and 2000 series aluminum alloy require a rapid quench to prevent heterogeneous precipitation from occurring during slower quenches resulting in reduced ageing response [6,7]. To achieve optimal strength, toughness, and corrosion resistance, it is desirable to retard the precipitation and diffusion process and keep the strengthening elements in solid solution until the alloy is age hardened. In general, "quench sensitivity" can be defined as the tendency for an alloy to form non-hardenable precipitates during quenching [8]. Quench sensitivity is important when forming thick section articles, as used in the aerospace industry, because the center may be weaker that the rest of the part due to slower cooling. Quench sensitivity of age hardenable aluminum alloys are dependent on various factors including alloy composition, processing, quenching type, quenchant media selection etc. Diffusion and precipitation kinetics are slower in some alloys than others, permitting lower cooling rates while still allowing high strengths and corrosion resistance to be obtained [8]. A large number of efforts have been made in the field of quench sensitivity and its mechanism. Previous work in the field of quench sensitivity has indicated that the Jominy end quench was first used to determine the hardenability of ferrous metals, and then developed to be applied to nonferrous alloys as well [9,10]. The Jominy end quench experiment consists of a cylindrical bar which is quenched at one end, resulting in a distribution of cooling rates throughout the bar [11]. Generally, the assessment of quench sensitivity for many heat treatable alloys has been investigated by correlating it with hardness measurements. More recently, non-destructive measurement of electrical conductivity has often been used to study the ageing process and the associated precipitation mechanism in many heat treatable Al alloys [12,13].

Similarly, electrical conductivity measurement can also be used to study the quench sensitivity during Jominy end quenching in heat treatable alloys and evaluate the extent of removal of the minor constituents from the solid solution at different locations along the Jominy specimen.

The accurate assessment of quench sensitivity for high strength 7000 and 2000 series Al alloys using non-destructive measurements of hardness and electrical conductivity becomes indispensable when these alloys are used for manufacturing thick section articles. This work aims to establish a modified process model for assessing the quench sensitivity of the 7000 and 2000 series aluminum alloys based on the Jominy end quench experiment, and to provide useful information for aluminum alloy design and for determining the impact of quench severity on properties and microstructure of aluminum products. Furthermore, transmission electron microscopy (TEM) work conducted on the selected specimens is to allow for a better understanding of the relationships between quench sensitivity and quench-induced precipitation formation.

2. Experimental Procedure

The chemical composition (wt.%) details of the selected alloys used in this work can be described as follows, AA2124 (Al-4.65Cu-1.55Mg-0.7Mn), AA2D70(Al-2.25Cu-1.45Mg-0.9Fe-0.9Ni), AA7B04(A1-6.25Zn-2.9Mg-1.6Cu-0.16Cr-0.31Mn), AA7050 (Al-5.9Zn-2.3Mg-2.15Cu-0.1Mn-0.1Zr) and a novel alloy (Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr). Round bars, 50 mm diameter, 150 mm long, were prepared from the received material to serve as Jominy end quench bars. The round bars had 2 mm diameter holes machined to its centre at different distance from the quench end in order to allow cooling curves to be obtained using 2 mm diameter type K thermocouples monitored using a data acquisition system. Solid solutionizing was conducted in electric muffle furnace and quenching took place in a modified apparatus, as illustrated in Fig.1. Samples were transferred from the furnace to the quench apparatus in less than five seconds. Once the bars cooled to below 50℃, they were removed, dried and divided into two half along the long direction using a linear cutting machine as soon as possible. One of the half was placed in a conventional freezer until the as-quenched electrical conductivity measurement was performed, and the other was ageing in a small box furnace to the desired temper prior to hardness testing.

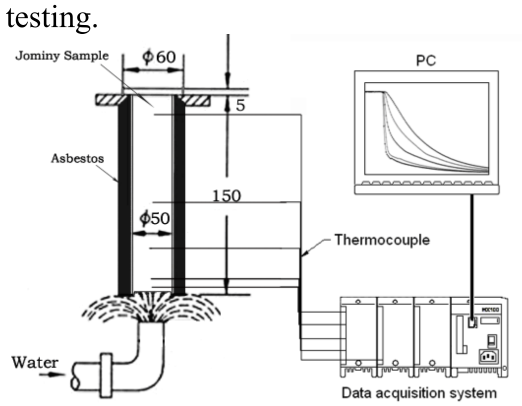

Fig.1 Schematic of the Jominy end quench test kit

Electrical conductivity measurement on each bar was carried out using a direct reading type conductivity meter based on eddy current principals. This meter (measuring in units of $Ms{\cdot}m^{-1}$) was calibrated against a standard, where 1 $Ms{\cdot}m^{-1}$=1.724 %IACS (International Annealed Copper Standard). Hardness testing was conducted using a digital Brinell hardness meter, which was calibrated against a standard. Hardness testing was conducted on each bar, two rows of Brinell hardness measurements were recorded at a distance of approximately 3 mm from the axial line at approximately 5 mm intervals from the quench end. TEM studies on some Jominy end quench samples by using a JEM-2000FX electron microscope, in order to study the relationships between quench sensitivity and quench-induced precipitation formation.

3. Results and discussion

3.1 Cooling curves

The Jominy end quench test was repeated three times to determine cooling curves and hence cooling rates for the four locations along the specimen can be calculated. Fig.2(a) indicates cooling curves at distances of 10, 30, 60 and 120 mm from the quenched end of the AA2124 sample. The average cooling rates between 400 and 300℃ at different locations from the quenched end can be achieved by using regression analysis. The results indicate that the average cooling rates of about 28.5 ℃/sec, 9.3 ℃/sec, 2.7 ℃/sec and 2.0 ℃/sec can be obtained at distances of 10, 30, 60 and 120 mm from the quenched end. The cooling curves of AA7050 specimens observed are similar to the measurements for AA2124 Jominy end quenched specimens, as shown in Fig.2(b). It can be seen that a relative cooling at the 10 mm of about 18.3℃/sec with cooling rates between 400 and 300℃ at 70 mm from the quenched end decreasing to 2.5 ℃/sec.

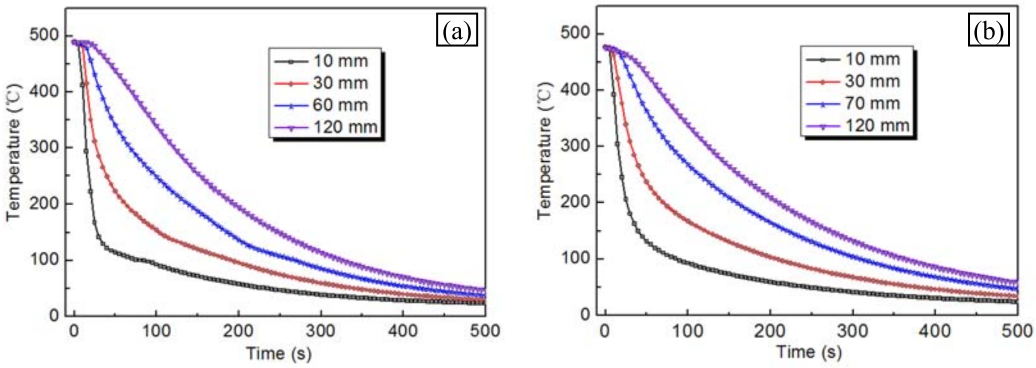

Fig.2 Cooling curves at different locations along the Jominy end quench specimen. (a) AA2124; (b) AA7050

3.2 Hardness and electrical conductivity curves from Jominy end quench

The quench sensitivity of some selected 2000 and 7000 series aluminum alloys have been evaluated using a method of Jominy end quench. The electrical conductivity and hardness profiles for selected 2000 series Al alloys were illustrated in Fig.3. As seen in the figures, electrical conductivity and hardness as a function of distance from the quenched end showed a reciprocal effect. The electrical conductivity of AA 2124 increased with the Jominy distance from 18.6 to 20.65 $Ms\cdot m^{-1}$, and decreased in as-aged hardness from 134.5 to 112 HB at locations of 5 and 150 mm from the quenched end, respectively. The results of the AA2D70 indicated the electrical conductivity and hardness values only vary by a maximum of 0.42 $Ms\cdot m^{-1}$ and 5.9 HB, respectively. Therefore, alloy AA 2D70 exhibited significantly less quench sensitivity than alloy AA2124. The results of a similar research conducted on various 7000 series aluminum alloys are illustrated in Fig.4. It can be seen that Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy exhibits the least quench sensitivity and alloy AA7B04 exhibits the greatest sensitivity.

If the 90% of the maximum hardness is defined as the depth of quenching, the depth of quenching can be obtained, as shown in Tab.1. The depth values of AA7B04, AA7050 and AA2124 Al alloy through Jominy end quenching are about 20, 55 and 55 mm, respectively. Meanwhile, the depth values of Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy and AA2D70 alloy are greater than 150 mm, which exhibits less quench sensitivity. It can be suggested that Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy and AA2D70 alloy are suitable to be made into large section plates or forgings without compromising strength and electrical conductivity in the center of the part after a relative slow cool.

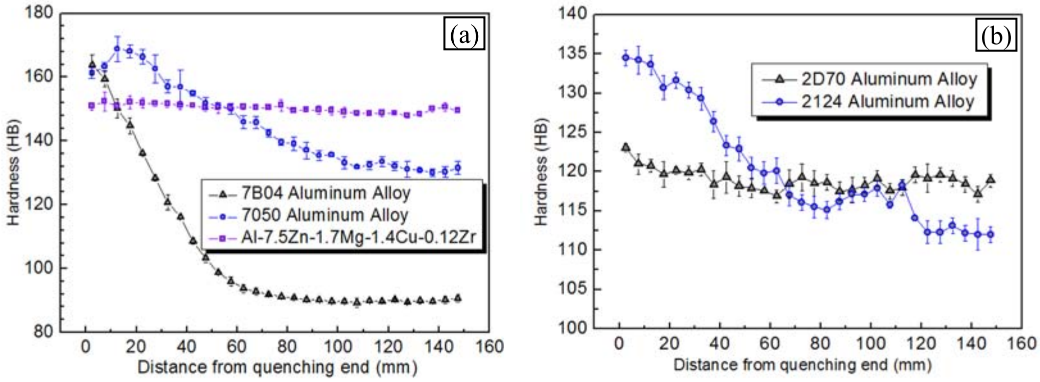

Fig.3 (a) Electrical conductivity in as-quenched and (b) hardness in as-aged as function of Jominy distance for selected 2000 series Al alloys

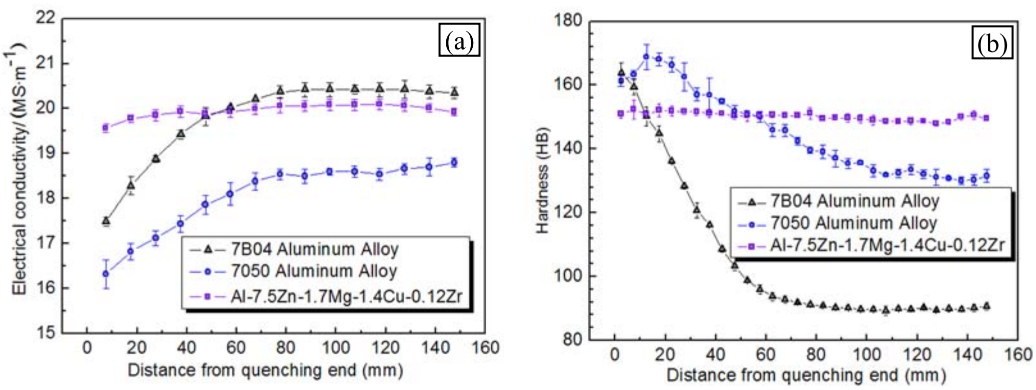

Fig.4 (a) Electrical conductivity in as-quenched and (b) hardness in as-aged as function of Jominy distance for selected 7000 series Al alloys

Tab.1 Comparison of maximum hardness and end-quench depth for selected Al alloys

AA	Maximum value of hardness (HB)	Depth value of 90%HB_{max} (mm)
2D70	123.0	greater than 150
2124	134.8	about 55
7B04	163.9	about 20
7050	168.8	about 55
Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr	152.4	greater than 150

3.3 TEM observations

As we known, alloying elements are kept in solution by quenching from the solution treating temperature, the objective of the solid solution treatment is to maximize the concentration of strengthening elements including zinc, magnesium, copper in the solid solution. Transmission electron images of AA 7B04 and Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy at positions corresponding to 5, 40, and 100 mm distances from the quenched end are shown in Fig.5 and Fig.6, respectively. It can be seen that there are remarkable differences in the nature of precipitates between AA 7B04 and Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy. The tendency for the AA 7B04 to form non-hardenable precipitates during quenching is significantly higher than that of Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy.

When AA7B04 slowly cooled from an elevated temperature, alloying elements are precipitated and diffused from the solid solution to concentrate at both grain boundaries and undissolved particles, as seen in Fig.5(b),(c). Cr and Mn-containing dispersoids are considered to play an important role for heterogeneous nucleation during slow quenching, which brings a lot of quench-induced η precipitates and significantly decrease the strengthening potential during ageing process. Certainly, lower the Zn:Mg ratio and higher Cu content should also be responsible for promoting quench-induced precipitation and increasing quench sensitivity. In contrary, no significant variations in precipitates inside the grains can be observed for the Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy when increasing the distance from the 5 to 100 mm from the quenched end, whereas excessively slow cooling allowed excessive concentrations of alloying elements to develop around the grain boundaries, as illustrated in Fig.6(c). Meanwhile, there are some coarse η precipitates nucleated inevitably on Al_3Zr dispersiods inside grains, but only in a few local grain areas, as shown in Fig.7.

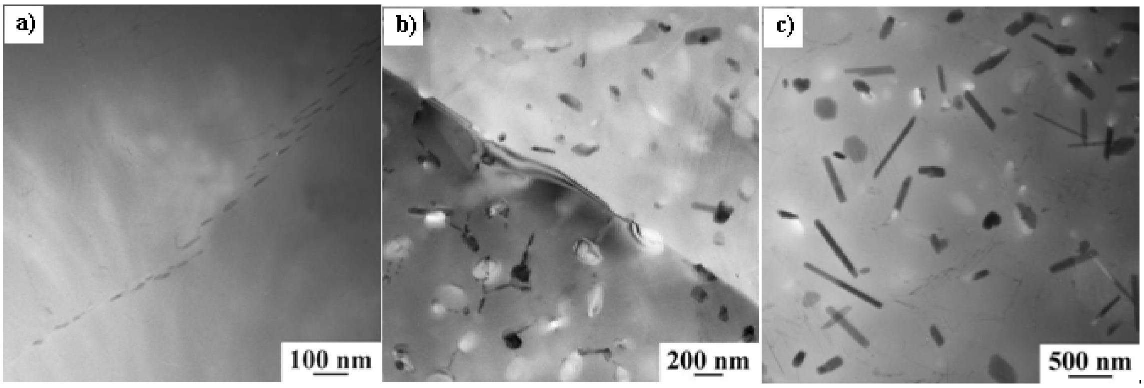

Fig.5 TEM images of precipitates of the as-quenched AA 7B04 at different locations from quenched end. (a) 5mm; (b) 40mm; (c) 100mm

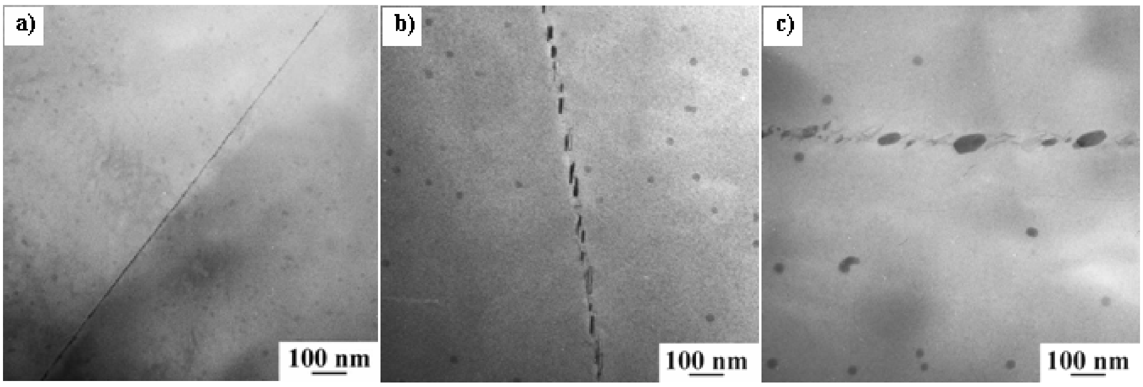

Fig.6 TEM images of precipitates of the as-quenched Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy at different locations from quenched end. (a) 5mm; (b) 40mm; (c) 100mm

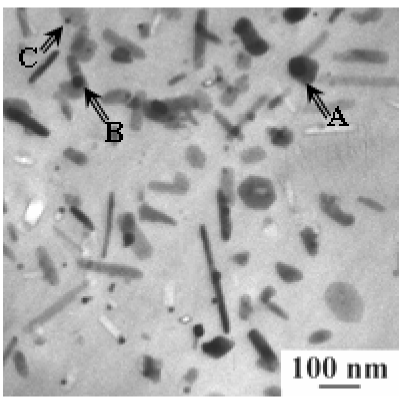

Fig.7 TEM image of quench-induced precipitates inside partial grain of Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy at 100 mm distance from quenched end

4. Summary

The demonstration quench testing system of Jominy End Quench for studying the quench sensitivity of heat treatable aluminum alloys has been established. Quench sensitivity and therefore the mechanical properties inhomogeneity in large plates or forgings can be predicted more accurately by the simultaneous combination of hardness and electrical conductivity measurements. The Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr and AA2D70 alloy exhibited the least quench sensitivity, but the AA7B04, AA7050 and AA2124 alloy were affected by cooling rate, and the AA7B04 was the most quench sensitive. TEM work indicates the tendency for the AA7B04 to form non-hardenable precipitates during quenching is significantly higher than that of Al-7.5Zn-1.7Mg-1.4Cu-0.12Zr alloy. The higher Zn:Mg ratio, lower Cu content and the use of Zr over Cr or Mn dispersoids should be explained primarily for creating a less quench sensitivity in 7000 series Al alloys.

Acknowledgement

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References

[1] D. Godard, P. Archambault, E. Aeby-Gautier and G. Lapasset: Acta Mater. 50 (2002) 2319-2329.
[2] S. Gang and C. Alfred: Acta Mater. 52 (2004) 4503-4516.
[3] E. A. Starke, Jr., E. Hornbogen: Aluminium Alloys, Ed. by J. Hirsch, B. Skrotzki and G. Gottstein, (WILEY-VCH, Weinheim, 2008) pp. 3-13.
[4] G. J. Wang, B. Q. Xiong, Y. A. Zhang, Z. H. Li and P. Y. Li: International Journal of Minerals, Metallurgy and Materials. 4/16(2009) 427-431.
[5] Z. H. Li, B. Q. Xiong, Y. A. Zhang, B. H. Zhu, F. Wang and H. W. Liu: Mater Charact. 59(2008) 278-282.
[6] D. A. Tanner and J. S. Robinson: Journal of Materials Processing Technology. 153-154(2004) 998-1004.
[7] A. Deschamps, G. Texier, S. Ringeval and L. Delfaut-Durut: Mater Sci Eng A. 501(2009) 133-139.
[8] G.E. Totten, G.M. Webster and C.E. Bates: *Quenching, Handbook of Aluminum*, (Marcel-Dekkar, Inc., New York, 2003) pp. 971-1062.
[9] C. Nowill: Investigation of the Quench and Heating Rate Sensitivities of Selected 7000 Series Aluminum Alloys. Dissertation, Worcester Polytechnic Institute(2007).
[10] A. Zehtab Yazdi, S.A. Sajjad, S.M. Zebarjad and S.M. Moosavi Nezhad: Journal of Materials Processing Technology. 199(2008) 124-129.
[11] ASTM A255, *Standard Test Method for Determining the Hardenability of Steel*, ASTM, (2007).
[12] Z. H. Li, B. Q. Xiong, Y. A. Zhang, B. H. Zhu, F. Wang and H. W. Liu: Mater Sci For. 561-565 (2007) 139-142.
[13] M. A. Salazar, Y. Y. Zhao, A Pitman and A. Greene: Mater Sci For. 519-521(2006) 853-858.
[14] B. Q. Xiong, X. W. Li, Y. A. Zhang, Z. H. Li, B. H. Zhu, F. Wang, H. W. Liu: *Aluminium Alloys*, Ed. by J. Hirsch, B. Skrotzki and G. Gottstein, (WILEY-VCH, Weinheim, 2008) pp. 861-867.