A NEW AND RELIABLE STATISTICAL APPROACH WITH EFFECTIVE PROFILING OF HARDNESS PRESERVING SAMPLES IN TIG-WELDING, THERMAL TREATMENT AND AGE-HARDENING OF ALUMINUM ALLOY 6061

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Abstract

Light metals and alloys are highly fascinated by aircraft industries due to their good strength-to-weight ratio, which is the prime requirement for aviation’s designers. Assembling of aircrafts components is often carried out using tungsten inert gas (TIG) welding, which is more acceptable for heat treatable aluminum alloys. We focus on the viable use of TIG welded assemblies of 6061 aluminum alloys to homogenize its hardness properties by heat treatment. Investigation proceeds by perceiving the effect of different precipitation hardening conditions on Aluminum alloy through their micro and macro-structural behavior and microhardness analysis. The statistical examination was conducted to evaluate the integrity of heat treated samples. A new and efficient measure – the coefficient of reliability – is introduced to outline the best hardness preserving samples. The statistical analysis shows the effectiveness of the coefficient of reliability to outline the best samples. The experimental results show that the samples aged at 175°C for 12 hours preserve the hardness profile of the welded alloy. The result is also verified from the mean hardness, coefficient of reliability and standard deviation values and in agreement with literature.

Keywords: 6061-Al-alloy, Tungsten inert gas welding (TIG), Precipitation hardening, Micro and macro structures, Microhardness, Statistical analysis

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I. Introduction

Aluminum alloy 6061 is one of the special heat treatable aluminum alloys that qualify the material characteristics set for aircraft and automotive industries. Besides other alloys, aluminum alloys mainly tailor their wide application due to optimum strength, lightweight, fatigue properties, good corrosion resistance and lower cost [I], [V], [XVIII]. These properties make aluminum alloys suitable for fuel efficient vehicles for the automotive and aerospace industries [XVIII], [XIV]. TIG welding is mostly used for aluminum alloys to assemble the structural parts by the industrial sector, because of cost-effectiveness, faster speed, reliability, and portability [IX], [XX]. The welding temperature produces inhomogeneity in the microstructure of the welded zone, HAZ and base metal, which results in non-uniform mechanical properties like strength, toughness and hardness within the material. This may lead to catastrophic failure of the material during service conditions [I], [X], [XIX], [V].

To avoid catastrophic failure, post welding heat treatment is the best option, which homogenizes the structure. Heat treatment temperature and time play a vital role in producing appropriate microstructural features and mechanical properties. Post welding heat treatment consists of two step cycle, 1. Solution annealing and 2. Age hardening. Pseudo-binary phase diagram for Al-Mg$_2$Si as shown in Fig. 1. can be used to determine the solution annealing temperature [XII]. Lot of research is being carried out by the researcher on post welding heat treatment particularly on age hardening temperature and time to achieve best mechanical properties [XI], [XXIV],[XXVIII],[XXII], [XXV],[XVI].

Fig 1. Pseudo-binary phase diagram for Al-Mg$_2$Si [V]

To verify the experimental results, researchers are focusing on the statistical analysis approach so that the result and conclusion must be objective oriented rather than hypercritical. Statistical analysis cannot show that a factor has a specific effect but deliver guidelines as to the reliability and validity of the results [XIII]. There are various statistical tools used in diverse experimental areas, which include mean, median, mode, standard deviation, variance, etc. For example, different statistical methods for gas explosion were reviewed elsewhere for the period 2001-2003 [III]. The statistical techniques to observe variations in the geometrical properties along the welded joints were discussed in detail in Pasqualini et al., with applications to marine and submarine civil engineering infrastructures [XV].

*Umair Aftab et al*
The past approaches have relied much upon the mean hardness of the post welded heat treated Aluminum alloy 6061 to categorize the best samples which have maximum hardness [II],[VII],[VIII]. Due to excessive fluctuations in the hardness profiles, the standard deviation also plays an important role. Consequently, one of the main contributions of the present research is to combine the concepts of mean and standard deviation in form of a new measure – the coefficient of reliability. We determine the effect of heat treatment on the microstructure and hardness distribution of TIG welded aluminum alloy 6061. The aging temperature selected for the particular study is 175°C at a various time intervals. The results were further verified by using statistical approaches. It is demonstrated that the coefficient of reliability along with mean plays an important role to outline the best hardness preserving samples.

II. Experimental Work

The research was conducted using an annealed aluminum plate of 10 mm thickness. The chemical composition of as-received material is stated in Table 1. Specimen of 25mm × 25mm size were cut from the plate, after that single bevel was made at one side of each specimen. The prepared samples were cleaned and washed by using a wire brush and acetone. Samples were welded using Tungsten inert gas (TIG) welding, argon gas was used as a shielding gas.

Table 1: Chemical Composition

| Element | Zn | Si  | Mg  | Mn  | Ti  | Cu  | Fe  | Cr  | Al   |
|---------|----|-----|-----|-----|-----|-----|-----|-----|------|
| Composition | 0.21 | 0.75 | 1.12 | 0.12 | 0.09 | 0.22 | 0.63 | 0.12 | Remaining |

Solution treatment (ST) of TIG welded specimens were carried out at 525°C (Model: Nabertherm, LT 40/12) after allowing 1 hr soaking time, samples were rapidly quenched in water. Later on the samples were artificially aged (AG) at 175°C for various time intervals as shown in Table 2. After heat treatment samples were ground, polished and then etched with a Keller’s solution (95% H2O + 2.5% HNO3 + 1.5% HCl + 1% HF). Weld and HAZ zones evaluation was conducted by using a stereomicroscope (Model: Metkon, IMM 901). The microstructural examination was carried out by using a metallurgical microscope (Model: Olympus, SZX16) at 100X. Hardness profile was developed at 1mm interval using 500g load for 15sec on micro Vicker hardness tester (Model: Wilson 402MVD).

Table 2: Sample IDs

| Sample Number | Sample ID | Heat treatment/Condition | Aging Time |
|---------------|-----------|-------------------------|------------|
| 1.            | UW-UT     | Un-welded condition     | Zero       |
| 2.            | W-UT      | Welded condition        | Zero       |
| 3.            | 175-AH-4  | Welded + ST (525°C) + AH 175°C | 4hrs     |
| 4.            | 175-AH-8  | Welded + ST (525°C) + AH 175°C | 8hrs     |
| 5.            | 175-AH-12 | Welded + ST (525°C) + AH 175°C | 12hrs    |
| 6.            | 175-AH-16 | Welded + ST(525°C) + AH 175°C | 16hrs    |
| 7.            | 175-AH-20 | Welded + ST (525°C) + AH 175°C | 20hrs    |

Umair Aftab et al
III. Proposed Coefficient of Reliability and Important Formulas for Statistical Analysis and Comparison

The past studies on the heat treatment of Aluminum alloys while welding in the literature have focused on the mean of the samples before and after treatment for outlining the best-welded sample. However, it is also important to account for the sample means on the basis of sample dispersions, mostly in terms of standard deviations. The standard deviations can have a larger impact on the observed means from samples, which is common knowledge in statistics and data analysis, as also highlighted in standard texts [XXVII],[XXX],[VI]. It is possible to have two samples with the same mean, but different variability levels, which determines their stability. In this case, the sample exhibiting less variability is more reliable, and the one with more variability is less reliable than the other. Since the mean microhardness of all samples is not supposed to be the same, so for reliability, the standard deviation alone is not sufficient.

In this work for the statistical analysis of the experimental data, we combine the concepts of the sample mean and sample standard deviation to devise a new formula for sample reliability. The new formula can be used as a standard in future studies.

If $H^{(j)}(x_i), i=0,1,…,8$ represent the microhardness (in HV) of the $j^{th}$ aluminum alloy sample at different positions, $x_i = ih$, where $h = x_{i+1} - x_i$ is the uniform spacing between any two successive positions where the microhardness is measured, then the mean hardness of the $j^{th}$ sample, $\mu^{(j)}$, can be defined as equation (1):

$$\mu^{(j)} = \frac{\sum_{i=0}^{i=8} H^{(j)}(x_i)}{9}, \quad j = 1,2,\ldots,7$$

(1)

The mean, $\mu^{(j)}$, specifies the average microhardness of the $j^{th}$ sample. It should be noted that the mean alone is often affected by outliers, if any, in the data. The standard deviation in the microhardness of the $j^{th}$ sample can be defined as equation (2):

$$\delta^{(j)} = \sqrt{\frac{\sum_{i=0}^{i=8} [H^{(j)}(x_i) - \mu^{(j)}]^2}{9}}, \quad j = 1,2,\ldots,7$$

(2)

It should be noted that the word sample used here in this study is used in a different context than the usual sample-population studies in statistics. Here, by samples, we mean different Aluminum alloys, before welding, after welding and after receiving heat treatment at 175°C with varied time (in hrs). For $j = 1,2,\ldots,7$, there are seven samples in total, as described in Table 1.

Different statistical formulae were used to deduce the reliability of microhardness profile with more accuracy and efficiency. Using the mean hardness ($\mu^{(j)}$) and the corresponding dispersion in terms of the standard deviation ($\delta^{(j)}$) of the $j^{th}$ sample, the coefficient of reliability ($a^{(j)}$) of hardness profile of the $j^{th}$ sample, can be defined as:

$$a^{(j)} = \left| \frac{\delta^{(j)}}{\mu^{(j)}} - 1 \right| \times 100, \quad j = 1,2,\ldots,7$$

(3)

Umair Aftab et al
Using (1) and (2) in (3), the coefficient of reliability can be found. The coefficient of reliability always falls in the range of 0-100%. The sample with a higher value of $\alpha^{(j)}$ then others will be considered more reliable than other samples. The reliability coefficient, equation (3) relies not only on the mean of the sample but also on sample dispersions, thus seems to be a balanced statistic to measure the reliability of the sample. The reliability percentage determines to how much extent the mean microhardness of a sample correctly represents the microhardness across all positions in that sample. It is possible to have a sample with a higher mean hardness than others but the worst reliability. So, preference will be given to a sample exhibiting not only a higher mean but also a considerable reliability coefficient.

It is also important that the welded samples after the heat treatment should exhibit a similar hardness trend as the un-welded and un-treated samples (UW-UT, i.e. sample 1). Shaikh et al. and Srbslav et al. used the definitions of relative percentage errors on the statistical analysis of the fluid flow friction factor equation to calculate the variation between the numerically simulated and estimated data $[XX]$, $[XXI]$, $[XXV]$. Similarly, to see the discrepancy in the microhardness of welded and heat-treated samples, i.e. samples 3-7 marked as (*), with the UW-UT sample (sample 1), the relative percentage error distributions can be computed across all positions $x_i$ using equation (4):

$$
\varepsilon_i^{(1,\ast)} = \left| \frac{H_i^{(*)} - H_i^{(1)}}{H_i^{(1)}} \right| \times 100 \text{, } i = 0, 1, \ldots, 8
$$

The percentage relative error distributions in equation (4) vary in the range 0 to 100%. A welded and heat-treated sample, for which these errors are smaller across most of the positions, is considered to have a closer hardness trend to that of the UW-UT sample. Equation (4) is also an efficient way of categorizing the samples in addition to the equations (1)-(3).

**IV. Results and Discussion**

**Macrostructure and Microstructure**

The stereo macrostructure of the welded specimen is shown in Fig. 2, which clearly reveals weld, HAZ and base metal zones. Weld appearance is approved in accordance with standard (SS-EN ISO 10042:2005) and did not show any hot cracking. The microstructure of an unwelded and untreated sample of Al-Alloy 6061 is shown in Fig. 3 (a), in which uniformly distributed precipitation of Mg2Si in the aluminum matrix can be seen. While typical non-uniform microstructure across base, HAZ and weld zone of welded and untreated sample is shown in Fig. 3 (b). This non-uniformity may lead to the non-uniform hardness distribution across the samples.
Fig. 2. Stereo macrograph of Welded 6061 Al- Alloy

Fig. 3. Optical Micrograph of 6061 Al- Alloy (a) unwelded (b) as-welded

Fig. 4 shows the microstructure of welded aluminum alloy after age hardening at 175°C at various time intervals. The phase Mg₂Si was the main component of 6061, which freely dissolved during solutionizing and contribute to the precipitation hardening for the period of artificial aging [II]. It is observed that by changing the aging time the microstructure is changing. During the increase in soaking time the undissolved or precipitated soluble phase constituents form a good homogenous solid solution. Prolong soaking time might be associated with the redissolution tendency.

**Micro-hardness Profiles**

Fig. 4 (a-e) shows the micro-hardness profile of the heat-treated samples as compared to unwelded and welded samples. It is evident from the result that there is a minor variation in the hardness profile of unwelded specimen, while after welding no uniformity in the hardness profile can be seen, due to the formation of HAZ zone. The graph demonstrated that, as the time changes for age hardening, the hardness profile also changes. Actually, this was predictable by the microstructure examination; during the increase in soaking time the new phases are precipitated. Increase in soaking time decreases the hardness which may be due to the redissolution of precipitated Mg₂Si. It is apparent from the result that the sample aged

*Umair Aftab et al*
at 175°C for 12 hrs has maximum mean hardness with low deviation in the hardness profile. Therefore, it is assumed that sample aged at 175°C for 12 hrs show the best results.

Fig 4. Optical Micrograph of welded Al- Alloy 6061 after heat treatment at (a) 175°C for 4hrs (b) 175°C for 8hrs (c) 175°C for 12hrs (d) 175°C for 16hrs (e) 175°C for 20hrs

Fig 5. Micro Hardness (reading profile) of sample (a) 175-AH-4 (b) 175-AH-8 (c) 175-AH-12 (d) 175-AH-16 (e) 175-AH-20

**Statistical Analysis of the Results**

Using the data of samples 1-7 as in Fig. 5 (a)-(e), the mean, standard deviation and reliability coefficient in the microhardness profiles of the samples have been computed using equations (1)-(3) and are depicted in Fig. 6. For further analysis, we have used the UW-UT sample as a reference, which has the maximum mean hardness

*Umair Aftab et al*
of 104.622HV and the minimum standard deviation of 2.526HV; also the highest reliability coefficient of 97.584%. After TIG welding as described in experimental setup in previous the section, the hardness profile of the UW-UT sample has compromised to a large extent with the worst decrease in the mean (78.577HV)) and increase in standard deviation (11.112HV) and smallest reliability coefficient (85.845%). By precipitation hardening and heat treatment at temperature 175°C and at different times with an interval of 4 hrs, we have been able to achieve an increase in the reliability of the samples up to a maximum 94.736%, all values are shown schematically in Fig. 6. In the similar fashion, it is evident from Fig. 6, that the mean hardness of samples 3-5 increases, whereas after that the mean hardness decreases with more heat longing heat treatment at the same temperature after 12 hrs. On the other hand, the standard deviations also change the trend before and after the sample 175-AH-12, i.e. sample 5.

The percentage relative error distributions in mean microhardness profiles of samples 3-7 with reference to sample 1 are shown in Fig. 7. It is clear that errors in microhardness values of sample 5 (175-AH-12) at almost all of the positions, except at 3mm and 4mm are smallest as compared to the error distributions of other samples. Fig. 7 also demonstrates the preference of Sample 5 over other samples to achieve maximum mean hardness with considerable reliability in hardness values and in uniformity with the reference hardness profile of UW-UT Aluminum alloy.

On the basis of the mean microhardness and corresponding reliability of the samples, sample 5 (AH-175-12) is considered the high hardness preserving sample, sample 6 (AH-175-16) is considered the moderate hardness preserving sample, sample 4 (AH-175-8) and sample 3 (AH-175-4) are considered average hardness preserving samples, whereas the sample 7 (AH-175-20) is below average hardness preserving sample.

Fig 6. Statistical Analysis (a) Mean (b) Standard Deviation (c) Coefficient of Reliability

Umair Aftab et al
Fig 7. Relative percentage errors in microhardness profiles of samples 3-7 with respect to sample 1 across different positions

V. Conclusion

The work focused on the effective use of TIG welded aluminum alloy 6061 to preserve hardness profile by heat treatment at the constant temperature 175°C with varying time intervals. The macro and microstructures of the heat-treated samples were examined and micro-hardness profiles were evaluated. To categorize the best hardness preserving samples, a new statistical measure, the coefficient of reliability, was introduced and found to be efficient for this purpose along with mean. Based on means, standard deviations and reliability coefficients of the heat-treated samples, and their relative percentage error distributions concerning the unwelded sample, it was observed that the age-hardened sample at 175°C for 12 hours resulted in the maximum mean hardness with considerable reliability.

Conflict of Interest:

Authors declared : No conflict of interest regarding this article

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