Empirical Relationship between Hardness and Tensile Properties of High Pressure Torsion-processed Al 6061

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Abstract. Improved strength is the ultimate goal of advanced material processing technique, including high-pressure torsion (HPT). To evaluate this goal, it requires determination of strength properties of the processed sample. While tensile test involves destructive test procedures, hardness is a closely related mechanical property in evaluating strength. This illustrates the need for a reliable hardness-tensile properties relationship. This paper determined an empirical relationship between hardness and several tensile properties i.e. ultimate tensile strength, Young modulus and tangent modulus, of HPT-processed Al 6061 samples. As results, an acceptable linear correlation for each property was obtained with a unique relationship. The degree of agreement between the studied properties and hardness was discussed. With recent advanced in computational method, the derived empirical relationships could optimise the HPT processing and aid the sample behaviour control and prediction.

1. Introduction

High pressure torsion (HPT) is a material strengthening technique through severe plastic deformation (SPD). The key SPD features includes introduction of a significant hydrostatic pressure and excessive strain with insignificant change in the overall sample dimensions [1–3]. As shown in Figure 1, HPT technique obtains these features by applying a simultaneous high compressive force and torsional straining. By restriction of material free flow, these forces subsequently induce micro-mechanical strengthening mechanisms to the processed sample, including grain size, precipitation, dislocation and solid-solution hardening [4].

Factors such as material and processing parameters affect the strengthening output. Therefore, evaluation of the strengthening level achieved by the specific HPT-processed materials is necessary. Uni-axial tensile test is a basic procedure to examine mechanical properties. However, engineers and researchers often conduct hardness test as a quick check on the strength properties [5]. It is comparatively non-destructive, fast, inexpensive and more effective for small-scale samples. This definitely requires an acceptable hardness-strength relationship. Previous researcher, Gasko and Roserberg [6] verified a greater possibility of tensile strength prediction by hardness measurement, as compared to yield strength, on dual phase (ferrite-martensite) steel.
Figure 1. Schematic diagram of a HPT process where a thin disc sample subjected to a simultaneous pressure ($P$) and torsion ($T$), until $n^{th}$ number of revolutions ($N$) at a determined rotational speed ($\omega$).

Some hardness-strength linear correlations have been previously reported [5–7]. The simplest developed correlation is the three-time general hardness-strength ($H$-$\sigma$) relationship, as shown in Equation (1).

$$H = f(3\sigma) \quad (1)$$

Zhang et al. [5] presented a hardness-strength relationship unique classification by material type and processing technique. In view of processing technique, it was shown that the relationship of Cu–Zn alloys deformed by Equal Channel Angular Pressing (ECAP) is $H \approx 3\sigma$ and $H < 3\sigma$ when subjected to HPT. In both cases, $\sigma$ represents the yield or tensile strength due to the limited work-hardening ability of the SPD-processed material. However, these generic relationships predict a very wide range of strength properties, particularly for the HPT materials.

Later, based on findings presented by number of researchers, Tiryakioğlu et al. [7] concluded that the hardness-strength relationship is better expressed in the form of non-zero $y$-intercept, as shown in Equation (2).

$$H = \beta_1 \sigma - \beta_2 \quad (2)$$

in which $\beta_1$ is the slope and $\beta_2$ is the $y$-intercept of the fitted linear correlation.

The discussed inconsistency led to the examination of a hardness-strength correlation for a specific processed material. While a number of literature reported on steel [6,8-10], to date, inadequate studies describing the specific correlation on aluminium alloy exists. This paper aims to obtain an empirical relationship between hardness and tensile properties of high pressure torsion-processed Al 6061.

2. Methodology

This paper studies an Al 6061 with material composition listed in Table 1. Disc with diameter of 10 mm and thickness of 1 mm was prepared. The pre-HPT samples were solution treated (ST) at 530°C for 4 hours in an air atmosphere and then immediately quenched into ice water. Each disc was processed by HPT using procedure as reported in previous literature [4], [11], at room temperature under quasi-constrained conditions with an applied pressure of $P = 6$ GPa for revolution up to 5, and a rotation speed of $\omega = 1$ rpm. The full revolution samples were then subjected to subsequent ageing at100°C in the air atmosphere for certain periods of time up to 15360 minutes, which is equivalent to 10.5 days.

Mechanical properties of aluminium alloy 6061 subjected to HPT was evaluated. Two mechanical tests were conducted which are uni-axial tensile test and hardness test. Figure 2 illustrates the locations for hardness measurements and tensile specimen on the 10 mm diameter HPT disc sample.
Table 1. Material composition of the studied Al 6061

| Measurement (wt%) | Mg  | Si  | Cu  | Fe  | Cr  | Zn  | Ti  | Al   |
|------------------|-----|-----|-----|-----|-----|-----|-----|------|
| Composition      | 0.96| 0.59| 0.29| 0.29| 0.02| 0.01| 0.01| Balance |

Figure 2. Locations for hardness measurements and tensile specimen on a HPT disc sample.

Note: Units: mm

The tensile test specimen having 1.5 mm gauge length, 0.7 mm width and 0.5 mm thickness were cut from the HPT sample using electrical discharge machining (EDM). Tensile tests were carried out at room temperature with an initial strain rate of $2 \times 10^{-3}$ s$^{-1}$. Tensile test generates properties such as yield stress, Young modulus, tangent modulus and ultimate tensile strength.

Whereas hardness tests, which measures the surface resistance against plastic deformation was conducted using Vickers test method. Vickers micro hardness was evaluated by application of a 100 g load for a dwell time of 15 s at equal distances of 1 mm from the disc centre along several radial directions. An average hardness value was calculated for each sample. Regression analysis was then conducted using the property values obtained by the tensile and hardness test.

3. Results and Discussions

Mechanical properties of the processed samples were presented in the first subsection. This will be followed by findings on the empirical relationship between hardness and tensile properties.

3.1. Mechanical properties of Al 6061

Figure 3 shows the engineering stress against engineering strain plot for the samples processed by HPT for 5 revolutions and subsequently aged at 100°C for several ageing durations. The stress-strain curve for pre-HPT sample was also included for comparison. Flow stress of the HPT-processed material exhibits work hardening while reducing some ductility. It can be clearly observed that the yield strength and tensile strength were significantly increased as compared to the ST sample. A similar behaviour of the HPT stress flow was reported in various materials including pure metals [12-14], alloys [15-16] and composite [17]. The properties were also affected by ageing duration.

Table 2 summarises the hardness and tensile properties of the studied samples. It can be seen that the highest strength of 622.2 MPa and hardness of 166 Hv were achieved in the 5 revolutions sample with subsequent ageing at 100°C for 15360 minutes. The minimum values of both strength and hardness are 534.0 MPa and 161.6 Hv respectively for 5 revolutions and 15 minutes aged sample. When there was an increase/decrease in tensile strength, the values of hardness increased/decrease accordingly. These patterns indicate that hardness proportionally affects the tensile properties. The following subsections discuss this properties relationship.
Figure 3. Stress-strain curves for the samples processed by HPT for 5 revolutions and subsequently aged at 100°C for several aging durations.

Table 2. Hardness and tensile properties of the studied samples

| Number of HPT revolution, N | Process         | Hardness, $H$ (Hv) | Tensile strength, $\sigma_{UTS}$ (MPa) | Young modulus, $E$ (MPa) | Tangent modulus, $E_t$ (MPa) |
|----------------------------|-----------------|---------------------|----------------------------------------|--------------------------|----------------------------|
| $N = 0$                    | Solution treated| 61.35               | 225.6                                  | 5000.0                   | 250.0                      |
| $N = 5$                    | As-HPT          | 163.9               | 613.0                                  | 8625.0                   | 3333.3                     |
|                            | HPT-Aging 15 min| 161.6               | 534.0                                  | 8333.3                   | 1428.6                     |
|                            | HPT-Aging 480 min| 162.9              | 552.9                                  | 8947.4                   | 2555.6                     |
|                            | HPT-Aging 15360 min| 166.0          | 622.2                                  | 10526.3                  | 4117.6                     |

3.2. Hardness and tensile strength relationship

Ultimate tensile strength ($\sigma_{UTS}$) is the maximum stress withstand by a material while being loaded. Comparison between pre and post-HPT showed that $H$ and $\sigma_{UTS}$ values were increased from the pre-HPT to the post-HPT. The pre-HPT (as annealed) data is referring to other published data, which are Al 3% Mg alloy [18] and Al 33% Cu alloy [19]. $H$ values for the pre-HPT samples are ranging between the 50 Hv to 100 Hv. This value was significantly increased to the range between 150 Hv and 250 Hv after sample was subjected to HPT. The process also raises $\sigma_{UTS}$ from less than 100 MPa to the upper range, between 450 MPa to 850 MPa.

Figure 4 shows the plot of hardness ($H$) against $\sigma_{UTS}$. Observation on the HPT-processed Al 6061 indicates that $H$ correlates linearly with $\sigma_{UTS}$. Comparison was also conducted on other HPT-processed aluminium alloy published data, which are Al 4 wt% Cu [4] and 5483 Al–5%Mg alloy [20]. As results, a similar linear correlation pattern was observed on these additional data.

In terms of $H$- $\sigma_{UTS}$ relationship, a distinctive pattern can be observed between the pre and post-HPT materials. It can be seen that the as annealed data are scattered along the three-time general hardness-strength relationship, as written in Equation (1). However, the work-hardened HPT materials
are significantly deviate from the three-time general relationship. The deviation, by means of hardness to strength ratios, is between the range of 0.25 and 0.36.

The HPT-processed materials still obey the linear relationship, with a lower gradient that yield a specific value of y-intercept. Table 3 presents the $H - \sigma_{UTS}$ relationship and the respective correlation coefficient for the observed materials. A strong linear correlation was obtained for each material with the minimum and maximum coefficient of 0.84 and 0.96, respectively. This result confirms that the HPT-processed aluminium alloys follows the linear non-zero $y$-intercept $H- \sigma_{UTS}$ relationship model, as expressed in Equation (2). This model is consistent with finding reported by Salazar-Guapiriche et al. [21], particularly on Al 7010 alloy.

![Figure 4](image)

**Figure 4.** Hardness ($H$) against $\sigma_{UTS}$ for several aluminium alloys.

**Table 3.** Hardness-tensile strength linear correlation of aluminium alloys

| Aluminium Alloy | Relationship, $H = \beta_1 \sigma_{UTS} + \beta_2$ | Correlation coefficient, $R^2$ |
|-----------------|-----------------------------------------------|-------------------------------|
| AlMg1SiCu (This study) | $H = 0.042 \sigma_{UTS} + 139.3$ | 0.957 |
| Al 4 wt% Cu alloy [4] | $H = 0.073 \sigma_{UTS} + 146.1$ | 0.844 |
| 5483 Al–5%Mg alloy [18] | $H = 0.059 \sigma_{UTS} + 163.7$ | 0.865 |

3.3. **Hardness and modulus relationship**

Young modulus, $E$ is the ability of a material to withstand elastic deformation with increasing forces, which determined by the slope of stress-strain curve in the elastic region. On the other hand, rate of stress changes over plastic strain defines tangent modulus, $E_t$. It represents the material resistance to deform plastically. Both moduli describe material rigidity or stiffness. High $E$ or $E_t$ value describe low material potential to be elastically or plastically deformed, respectively.

Figure 5 shows the graph of modulus versus hardness for samples processed by HPT through 5 revolutions and aged at several ageing durations, as summarised in Table 3. It can be observed that
with increasing hardness, the Young modulus and tangent modulus increase. This pattern demonstrates that the hardness is related to the modulus parameters. It is a linear function of both the elastic and plastic parts. The linear regression for each modulus was indicated in the corresponding graph.

In comparison, difference in tangent modulus for samples that have undergone dissimilar hardening treatments is more apparent than Young modulus. This behaviour was described by the higher $H-E_t$ linear correlation slope, 606, compared to the $H-E$, 475.7. For a clearer comparison, Figure 6 shows the plot of normalised modulus ($\tilde{E} = E/E_{\text{max}}$ and $\tilde{E_t} = E_t/E_{\text{max}}$) against hardness. This graph explains the response of $E$ and $E_t$ against changes in $H$, in a similar data range. Modulus data that correspond to the same hardness value are referring to the similar sample that has undergone specific process. It can be clearly observed that the gradient of normalised tangent modulus against hardness is steeper than the Young modulus. This result implies that hardness has a greater detection of changes in the $E_t$ than $E$.

The observed trend may due to the hardness and tangent modulus measurement itself, which correspond to the plastic deformation. Hardness, which is a measure of a material's flow resistance to dislocations movement, describes the degree of plastic deformation in materials. Meanwhile, tangent modulus describes material potential to be plastically deformed. This could also be the factor of better tangent modulus approximation by hardness. The high value of correlation coefficient, $R^2$ for $H-E_t$ relationship, which is 0.96, reflects that $H$ and $E_t$ has an excellent agreement.

These correlations will benefit to determine an appropriate material model in computational mechanics. In order to simulate an HPT process for a particular sample, the material plasticity model requires a value of $E$ and $E_t$ as the parameter input. Through a simpler test, by measuring hardness, the value of $E$ and $E_t$ for the Al 6061 can be appropriately determined by the developed correlation relationship. An accurate model allows a better prediction of the material behaviour with HPT loading.
4. Conclusion
The empirical relationship between tensile properties and hardness of HPT-processed Al 6061 has been developed. This study showed an increase in material strength and rigidity with the increasing hardness. The HPT-processed aluminium alloys results including Al 6061, Al 4 wt% Cu and 5483 Al–5%Mg alloy, indicate that the strength correlates linearly over a hardness range with a non-zero y-intercept pattern. The calculated correlation are

\[ H = 0.042\sigma_{UTS} + 139.3 \]

for Al 6061 alloy,

\[ H = 0.073\sigma_{UTS} + 146.1 \]

for Al 4 wt% Cu alloy and

\[ H = 0.059\sigma_{UTS} + 163.7 \]

for 5483 Al–5%Mg alloy.

Hardness of the studied Al 6061 alloy also correlates well with Young modulus and tangent modulus. The relationship is linear, which are

\[ E = 475.7H - 68716 \]

and

\[ E_t = 606.0H - 96267 \]

for the respective modulus. Higher gradient of the \( E_t \)-\( H \) relationship, 606.0, as compared to 475.7 for the \( E \)-\( H \) relationship showed that hardness has a better detection of changes in tangent modulus, with a strong correlation of 0.96. The similar nature of plastic deformation measurement in hardness and tangent modulus might be the reason. These findings confirm that hardness is an appropriate alternative indication of the underlying mechanical properties of the HPT-processed Al 6061 alloys.

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