Lattice Strain In Aluminium After Plastic Deformation Process at A Cryogenic Temperature

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Abstract. Aluminium is a lightweight metal that is difficult to improve its mechanical properties. High plastic deformation on aluminium makes mechanical properties increase slightly. Aluminium at low temperatures has a lower inter-atomic spacing than at room temperature. Deformation at a cryogenic temperature is expected to increase the mechanical properties higher than at room temperature. The increasing mechanical properties is caused by increasing deformation density. The dislocation density of the aluminium can be predicted by measuring the lattice strain. In this paper, we used X-ray diffraction to measure the lattice strain. The aluminium used in this study was pure industrial aluminium, with a size of 10 x 10 mm and a length of 100 mm respectively. The plastic deformation process was carried out at -75 ºC using the impact test apparatus. The results of lattice strain measurement were verified through microhardness testing. The measurement showed that the plastic deformation process at a cryogenic temperature increased the lattice strain; this complies with microhardness measurement.

1. Introduction
Aluminium is a lightweight metal with a specific gravity 2.7 gram/cm³[1]. Aluminium is widely used such as household appliances, motor vehicles to aeroplane structure. The need for aluminium with stronger mechanical properties is accomplished by the addition of alloying elements. The addition of this alloying element can increase the strength of aluminium, such as the 2XXX series which is widely used in aircraft industry, the 6XXX series is widely used in bicycle, and aluminium alloy 7XXX series which is widely used in aircraft and bicycle[2].

The addition of alloying elements to aluminium causes the decline of other aluminium properties, especially corrosion resistance[3]. Another way to strengthening aluminium is to reduce the grain size, aluminium with smaller grain size has a higher tensile strength[4]. According to the law of Hall-Petch, the smaller the grain size the stronger the metal [5][2]. Metals with a very small grain size exhibit not only high tensile strength and hardness but also high ductility[6][7].

The process to reduce grain size on aluminium cannot be done by dynamic re-crystallisation processes such as in steel because aluminium has a very high stacking energy[1]. The re-crystallisation process of the metal can only be carried out when the metal has sufficient internal energy[8][9][10].

Plastic deformation can increase the stored energy in the aluminium. The amount of stored energy depends on plastic deformation; high plastic deformation causes an increase in the stored energy in
aluminium. The crystallisation can be done if the stored energy is high enough [11]. Increasing stored energy in aluminium to be sufficient for the recrystallisation process can only be done by providing very large plastic deformations.

The stored energy required for the recrystallisation process can be obtained by rolling process or by ECAE process. In the process of rolling required a very high strain to obtain energy in a large enough [1][12], while the ECAE process required a huge pressure and cannot be done for bulk material [13].

The deformation process at low temperatures has higher hardness than the process at room temperature. In this research, the deformation process was done at -75 °C. This process was done to determine the effect of process temperature on lattice strain. Lattice strains were measured by X-ray diffraction. Lattice strains can be used to determine dislocation density changes. Dislocation density is associated with the hardness of metals; high dislocation density on metals results in metals with high hardness. Verification of lattice strain is done by hardness testing on the workpiece.

2. Material and Methods

Aluminium used in this research was pure industrial aluminium; the aluminium composition can be seen in Table 1.

| Table 1 Aluminium Composition |
|-----------------------------|
| Element | Amount (%) |
| Fe     | 0.0471     |
| Mn     | 0.0128     |
| Si     | 0.4801     |
| Cr     | 0.0020     |
| Ti     | 0.0510     |
| Al     | Balance    |

Aluminium for workpiece was cut in a size 10 x 10 mm and length of 100 mm (see Figure 1). Prior to the experiment, the aluminium was annealed at 450 °C for 30 minutes. The annealing process was carried out to remove residual stress in aluminium caused by the previous process.

Deformation process on aluminium was done by Charpy impact test apparatus. The Charpy impact test apparatus was used because the deformation process was carried out at very low temperatures.
Thus, the deformation process required high strain rates to reduce the temperature difference during the deformation process.

Before testing, the aluminium was dipped in alcohol mixed with liquid nitrogen. The temperature of this solution could reach \(-200\) °C. After the aluminium was immersed for 2 minutes, it was placed in the test apparatus, and its temperature was measured by a thermometer. When the aluminium temperature reached \(-75\) °C, the load (pendulum) on the impact test apparatus was removed.

The plastic deformation process was done by the impact test apparatus; this process caused the workpiece to bend and the workpiece strain can be calculated by the following equation.

\[
e_a = e_b = \frac{1}{(2R / h) + 1}
\]  

(2)\[12\]

Where  
\begin{align*}
R &= \text{radius bending} \\
h &= \text{thickness (position) of measurement}
\end{align*}

The macro-hardness of aluminium after the annealing process was measured by the Rockwell-B. In this method, we used a minor load of 10 kgf, primary load of 60 kgf and loading duration of 30 seconds. This test was also performed on aluminium after the plastic deformation process. The position of the macro hardness testing can be seen in Figure 2.

![Fig. 2. Macrohardness test position on aluminium after deformation processes](image)

The micro hardness measurement was performed on the cross-section of the workpiece after the deformation process. This measurement was performed to determine the distribution of micro hardness. The position of this micro hardness testing can be seen in Figure 3. Measurements were carried out with a load of 200 grams and indented in 30 seconds.

![Fig. 3 Position of microhardness testing](image)
After micro-hard testing, the workpiece was also observed by X-RD; the observation position was as the same as the micro hardness test position. The observation were conducted to determine the lattice strain in aluminium after the deformation process. The lattice strain in the metal showed that the dislocation density occurred; large lattice strain indicated higher dislocation density.

Lattice strain in aluminium was measured with Full Width at Half Maximum (FWHM) of X-RD diffraction. The FWHM measurement at peaks occurred at a particular angle at graphics resulted from X-RD diffraction. FWHM measurements can be seen in Figure 4.

![FWHM Measurement](image)

The lattice strain calculation was done by the following equation

$$B_s = \eta \tan \theta$$  \hspace{1cm} (1)[14]

Where:

- $B_s$ = line broadening
- $\eta$ = lattice strain
- $\tan \theta$ = tan of Bragg Angle

3. Result and Discussion

The aluminium workpiece after the plastic deformation process using impact testing machine at a cryogenic temperature can be seen in Figure 5.

![Aluminium sample after the deformation process](image)

Makro hardness testing was done on the aluminium before, and after deformation process, the macro hardness testing can be seen in Table 2
### Table 2: Macrohardness of Aluminium Hardness Deformation Process

| Sample | 25°C | -75°C |
|--------|------|-------|
| 1      | 57.0 | 70.0  |
| 2      | 56.0 | 71.0  |
| 3      | 56.0 | 69.0  |
| 4      | 56.0 | 71.0  |
| **Average** | **56.3** | **70.3** |

Macro hardness at the corner of the workpiece showed a considerably higher increase in hardness. The macro hardness was 56.3 HRH at 25 °C and 70.3 HRH at -75 °C. The difference in hardness indicated that the characteristics of aluminium at a cryogenic temperature and room temperature were different. The details of the characteristics of aluminium deformed at a cryogenic temperature can be revealed with micro hardness tests and X-RD diffractions.

The results of micro hardness testing on aluminium cross-section can be seen in Table 3.

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Macro hardness at the corner of the workpiece showed a considerably higher increase in hardness.

The hardness testing results of the deformed aluminium showed that the highest hardness occurred in sample 1 and 5. Sample 1 and 5 were the outer and inner side of the workpiece, which received the highest strain. Larger strains increased workpiece hardness. This phenomenon occurred in the deformation process at temperatures of 25 °C and -75 °C.

The hardness of deformed aluminium at a temperature of -75 °C was higher than that at 25 °C. The increasing aluminium hardness was due to an increase in dislocation density. At low-temperature dislocations are more difficult to move; low temperatures deformation cause increased hardness of aluminium.

The results of X-RD diffraction on aluminium after the deformation process can be seen in Figure 7.

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The peak position and FWHM for aluminium deformed at 25 °C and 75 °C can be seen in Table 3.
Table 3 X-RD diffraction pattern peak (2θ)

| Specimen | 25 °C | -75 °C |
|----------|-------|-------|
|          | Peak 2θ | Bs (°) | 2θ | Bs (°) |
| 1        | 1 38.94 | 0.2132 | 38.76 | 0.3625 |
|          | 2 45.14 | 0.3188 | 44.92 | 0.2949 |
|          | 3 65.50 | 0.3316 | 65.32 | 0.3310 |
|          | 4 78.66 | 0.4289 | 78.48 | 0.4288 |
| 2        | 1 38.86 | 0.2291 | 38.90 | 0.3017 |
|          | 2 45.06 | 0.2504 | 45.04 | 0.2865 |
|          | 3 65.36 | 0.3464 | 65.38 | 0.3668 |
|          | 4 78.50 | 0.3497 | 78.55 | 0.4782 |
| 3        | 1 38.92 | 0.1993 | 38.80 | 0.2380 |
|          | 2 45.40 | 0.2324 | 44.90 | 0.2946 |
|          | 3 65.44 | 0.2690 | 65.22 | 0.3916 |
|          | 4 78.58 | 0.3617 | 78.46 | 0.4539 |
| 4        | 1 38.90 | 0.2418 | 38.66 | 0.3110 |
|          | 2 45.12 | 0.2472 | 44.81 | 0.2884 |
|          | 3 65.48 | 0.3213 | 65.20 | 0.3465 |
|          | 4 78.62 | 0.3866 | 78.36 | 0.4554 |
| 5        | 1 38.82 | 0.2242 | 38.92 | 0.3212 |
|          | 2 45.18 | 0.2505 | 45.14 | 0.2861 |
|          | 3 65.44 | 0.3518 | 65.48 | 0.3969 |
|          | 4 78.63 | 0.4227 | 78.83 | 0.4699 |

The lattice strain in aluminium was calculated using equation (1). The result of calculation of lattice strain in aluminium after the deformation process can be seen in Figure 8.

The lattice strain in the deformed aluminium (Figure 8) showed that the deformation process at the cryogenic temperature resulted in larger lattice strain. Total of deformation occurring in aluminium affected the lattice strain; the higher the deformation, the higher the lattice strain. The increasing lattice strain phenomenon occurred at 25 °C and a cryogenic temperature. Cryogenic temperatures change the characteristics of aluminium. Also, dislocations in aluminium are more difficult to move; this causes the dislocation density to increase. Higher dislocation density makes higher lattice strain.

4. Conclusion
The lattice strain in the aluminium deformed at a cryogenic temperature was higher than that deformed at room temperature. The micro hardness testing on aluminium also showed that the
aluminium deformed at a cryogenic temperature was harder than that deformed at room temperature (85 HRH vs 55 HRH).

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