Size Effect on Deformation Characteristic of Aluminum under Impact Loading Condition

Hairul Arsyad¹, ING Wardana², Wahyono Suprapto³, Anindito Purnowidodo⁴

¹¹ Hasanuddin University, Mechanical Engineering Department, Engineering Faculty, 90245, South Sulawesi
¹, ², ³, ⁴ Brawijaya University, Mechanical Engineering Department, Engineering Faculty, 65145, Malang Indonesia

Abstract

Effect of specimen size and grain size on deformation characteristic of aluminum under impact loading conditions at constant impact energy per unit area has been studied experimentally. The friction effect was minimized with oil lubricant. The result shows that there are two significant differences in deformation characteristics due to size effect. The first is deformation in the thickness cross section of the coarse grain size specimen was not uniform and showed clearly barreling effect compare to the fine grain sizes. The second is deformation at the edge of the specimen with fine grain sizes has smaller grain flow lines and more uniform than the specimens with coarse grain size. The significant difference is mainly attributed to the differences on the number of grain boundary that act as deformation barrier. The grain size, however, does not have significant effect on the circularity since the specimen diameter is very large compare to the grain size. The circularity increases with increasing thickness of the initial specimen.

Keywords: size effect, deformation characteristic, barreling effect, grain flow lines, circularity.

Introduction

Development of the manufacturing technology components that lead to the miniaturization of products has increased significantly. Many components in the form of micro-parts have been found in the industry of mechanical devices [1]. The technique of making micro-size components also has been developed including photolithography, photochemical, micromachining, and etching process. However, the disadvantage of these processes is the high cost and long duration time [2]. Metal
forming becomes a promising option for making micro size product. Manufacturing process at this scale is called micro-forming. The shape of the metal was changed by plastic deformation into the desired product. This method is suitable for mass production and increase the strength of the material after forming process also more efficient on materials [2, 3, 4].

However, the problem encountered in the micro forming is a change in the deformation behavior of the material. This problem is known as the size effect [2, 3, 5, 6]. In order to observing the size effects in miniaturization, many researchers used the ratio of the size of the work piece to the grain size of the material. This ratio was varied to see the deformation behavior.

A lot of study has been done in examining the behavior of deformation due to the size effect. The research on micro - bending was conducted by Li et al. [7] for CuZn37 foil with variation of foil thickness. The micro-formability test was conducted by Kang et al. [8] by the micro - forgings of Al5083. Deng et al. [3] also examined the surface deformation by compression forming. Chan et al. [2] examine the deformation behavior of the micro - cylindrical compression test and micro - ring compression test. The study of deformation behavior and formability on this scale has been done with many types of testing including tensile test [9], bending test [10], compression test [2, 3, 8], and stretching test [11].

Although efforts have been conducted associating with the size effect on the micro forming focused on deformation behavior [3, 12, 13], flow stress behavior [2, 9, 11, 13], formability behavior [2, 6, 14], fracture behavior [10, 11, 13], surface deformation behavior [2, 3, 6, 11, 13], and the hardness behavior [6, 12, 15, 16], however, in the impact load conditions there are many problems still need a clearer understanding. This research is important as represent of drop forging applications in this scale. The aim of this study is to get a better approach of the role of size effect on deformation behavior and surface topography under impact loading condition.

Material and Methods
The commercially cylindrical aluminum (diameter 12 mm)with high content of aluminum was selected as testing material and the composition of the material taken from XRD is shown in table 1. Before impact loading, the specimen is pulled up to the length of 5 % and then heated up to temperatures of 350°C. Variations in holding time in the furnace are 30 minutes and 120 minutes in order to obtain two different grain sizes. The average grain size (d) was measured by Intercept method (ASTM E112). Two different grain sizes were obtained from heat treatment process which is d=110.8 μm and d=190 μm as shown in Figure 1.

Table 1: Testing material composition. Quantitative analysis results (RIR)

<table>
<thead>
<tr>
<th>Phase name</th>
<th>Content(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum, syn</td>
<td>98.9</td>
</tr>
<tr>
<td>Cristobalite beta</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Size Effect on Deformation Characteristic of Aluminum

The size and shape of testing material is shown in Figure 2. The deformation behavior due to size effect was observed experimentally in an impact test apparatus using a drop weight test as schematically shown in Figure 3. The weight of the applied load is 5 kg. The test was conducted by using oil lubrication between specimen and the punch. Machining process performed on specimens to vary the diameters ($D_o$) as: 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm and thickness ($t_o$) as: 0.5 mm, 1 mm and 1.5 mm. Table 2, show the number of specimen and the impact distance for each diameter of the specimen that to be dropped to give the same impact energy per area (1.12 Joule/mm$^2$). The changes of thickness and surface topography due to impact loads were measured with optical microscope and SEM. Deformation circularity was measured by a software aid known as ImageJ. The ImageJ software has a facility to measure perimeter, area and circularity level of any shape using photograph of the specimen.

Figure 1: a. Coarse grain (equivalent of grain size 190 μm) b. fine grain (equivalent of grain size 110.8μm)

Figure 2: Specimen shape and size.
Table 2. Number of specimen and the impact distance for each specimen.

<table>
<thead>
<tr>
<th>No</th>
<th>t₀</th>
<th>Number of specimen (pieces)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D₀=2mm</td>
</tr>
<tr>
<td>1</td>
<td>0.5 mm</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>1.0 mm</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>1.5 mm</td>
<td>5</td>
</tr>
<tr>
<td>Impact distance</td>
<td>72 mm</td>
<td>162 mm</td>
</tr>
</tbody>
</table>

Results and Discussion

Figures 4 shows the thicknesses and % deformation of the specimen after impact load for fine grain size (110.8 μm) and for coarse grain size (190 μm). The degree of deformation (% deformation) was calculated by the following equation [17]:

\[
\% \text{ Deformation} = \left(\frac{t₀ - t_i}{t₀}\right) \times 100\%
\]  

(1)
Where $t_i$ is initial thickness and $t_f$ is final thickness.

Figure 4a shows that with the same initial thickness ($t_0$), specimens with coarse grain size produces inconsistencies in thickness after impact loading compared to specimens with fine grain size. Figure 4 b show the result of % deformation for fine grain and coarse grain. It is found that for fine grain, the deformation tend to homogenous compare with the coarse grain. The homogenous deformation is a result of uniform thickness after deformation.

![Graphs showing thickness and % deformation for coarse and fine grain](image)

Figure 4: The thickness (a) and % deformation (b), after impact loading for coarse grain and fine grain
The effect of grain size on deformation behavior can be explained from the viewpoint of the number of grains which is involved in deformation. As illustrated in Figure 5, specimen with coarse grains has a number of grains less than the specimens with fine grains. It has been reported by Gau et al. [8] that the behavior of individual grains will be more dominant in the coarse grain size when the specimen size is reduced. The study by Kang et al. [7] found, that the deformation behavior at the micro scale is closely related to the number of grains involved in deformation process. Fu et al. [12] also explain that reduction of the size of the specimen and increasing the size of the constituent grains makes shape and orientation of the grains become very significant in controlling deformation. As a result, strain is not uniform and the deformation becomes more anisotropic [12].

Figure 5: Illustration of specimen cross-section before and after impact loading: a. coarse grain constituent; b. fine grain constituent.

The different thickness profile after impact loading between coarse grains and fine grains specimen also can be explained by barreling effect. It is well known that when a solid cylinder circular under compression state, the barreling effect is produce due to friction between specimen surface and the tooling. The barreling effect becomes appear because the material flow on the top and the bottom specimen surface is restricted by friction as illustrated in Figure 6. Although the lubricant is applied on the tooling-specimen interface, the friction on contact surface cannot be totally eliminated. This leads to the occurrence of the barreled side profile on the compressed specimen.
Figure 6: Barreling effect of compressed specimen.

Figure 7a show cross section of the specimen after impact loading for fine grain size. It can be seen that the cross section has high uniformity. It indicate that the specimen with fine grain size tend to have more homogenous deformation. The cross section pictures also verify the result from figure 4. Instead, Figure 7b shows cross section for coarse grain size. It can be seen that the cross section for coarse grain size tend to has non-uniform thickness. The difference in the thickness of the center and the edges produce the barreling effect.

Figure 7: Cross section profile of the specimen after impact loading shows the barreling effect: (a) fine grain size; (b) coarse grain size.

The Hall-Petch relation can be used to explain the deformation behavior related to the grain size [17]:
\[ \sigma = \sigma_i + k d^{1/2} \]  

\( \sigma_i \) and \( k \) are constants and \( d \) is the grain size. Based on Hall-Petch equation, the specimen with coarse grain size has low yield strength, and as a result the specimen with coarse grain having low flow stress. During deformation by impact loading, the specimen with low flow stress produce different deformation rate between surface area and middle area due to the friction at the surface. In other word, deformation at the middle of the specimen becomes easily and producing high deformation. This non-uniform material flow creates significantly barreling effect.
Effect of grain size also shows on deformation morphology at the edge of the specimen as shown in Figure 8. The difference of deformation morphology between fine and coarse grain size is also indicating different deformation behavior due to size effect. It is shown that deformations at the edge of specimen are different in grain flow lines and morphology between coarse and fine grain (Figure 8a and 8b). The size of grain flow lines is relatively larger and non-uniform for coarse grain. Specimen with fine grain has small grain flow lines and relatively uniform compare to the coarse grain. The grain size also contributes to the strength of the material. Specimen with fine grain has greater strength due to many grain boundaries that can act as a barrier of deformation. Specimens with more grain boundaries causes the material flow becomes more difficult but on the other hand deformation more homogeneous.

Figure 8c show deformation morphology at the edge for coarse grain with 1.5 mm initial thickness. Figure 8a and 8c shown that for the same grain size but different in specimen size, the deformation morphology is different. The deformation at the edge is relatively more uniform by increasing specimen thickness. This is indicating that specimen size also gives different effect to deformation in miniaturization. By increasing specimen size, the numbers of grain that involve in deformation also increase. It has been state by Kang et al [7] that, the deformation behavior at the micro scale is related to the number of grains involved in deformation process.
**Figure 8**: Effect of grain size on deformation morphology at the edge of the specimen ($D_0 = 2\text{mm}$): (a) coarse grain, ($t_0 = 0.5\text{mm}$); (b) fine grain ($t_0 = 0.5\text{mm}$); and (c) coarse grain ($t_0 = 1.5\text{mm}$)

In order to see more clearly the relationship between the size effect on deformation behavior, circularity was used as a base for the dimensional accuracy of a circular shape. The specimen with circular shape was chosen in this test. Testing is done with a drop tower test model and using open mold (open die). Uniformity of deformation is determined based on the level of circularity after impact loading. Circularity value can be estimated as using the formula [18]:

$$\text{Circularity} = 4\pi \left( \frac{\text{Area}}{\text{perimeter}^2} \right)$$

The above expression implies that circularity decreases with increasing specimen perimeter. For homogenous deformation, impact loading on the circular specimen could make deformation keeping its circular shape. This is because of the ideal deformation characterized by a uniform strain in the same value in all directions. By using a circular-shape specimen and using open mold (open die) then the value of circularity after impact loading can be used as measure of the degree of uniformity of deformation. The lower the value of circularity produced, the lower the uniformity of the deformation. Figure 10 shows the model of deformation due to impact load.
Figure 10: Model of deformation after impact loading, a. Homogenous/uniform deformation (circularity = 1), b. Non-homogenous deformation (circularity < 1).

Figure 11 shows the results of the average circularity. It is found that for the same specimen size, the average circularity was not much different for fine and coarse grain. It indicates that the grain size has no significant effect on circularity, see Figure 12. This is in contrast with the results obtained from thickness measurement after impact loading. It implies that deformation behavior in the radial direction due to impact loading is similar between fine and coarse grain size. It can be explained that there are more grain involved in the radial direction compare to the thickness direction. The role of size effect is not dominant in circularity because of \( D_o/d \) higher than \( t_o/d \), the size of the specimen diameter was not small enough to give a different deformation behavior.

Figure 12 show surface topography of the smallest specimen (\( D_o = 2 \text{ mm} \)) after impact loading. It is observed that there are similar surface topography and circularity for fine and coarse grain size. It is also found that, by increasing \( t_o \), the circularity increases.
Figure 11: The average circularity for fine and coarse grain size.

Figure 12: Surface topography and circularity of specimen after impact loading ($D_o = 2\text{mm}$); (a) Fine grain specimen; (b) Coarse grain specimen.

Conclusions
The size effects on deformation of aluminum under impact loads condition has been studied experimentally. The conclusion that can be induced from the study are as follows:

The role of size effect on deformation behavior due to impact loads can be seen from the thickness after impact loads and % deformation. Specimens with coarse grain size produces inconsistencies in thickness and deformation after impact loading compared to specimens with fine grain size. The smaller specimen dimension with larger grain size causing the number of grain that involve in deformation decrease.
The behavior of individual grains becomes significant in the specimen with coarse grain that led to non-uniform thickness. Thickness after impact loading becomes more uniform for fine grain. Size effect is also seen on deformation morphology at the edge of the specimen. Circularity as geometric parameters that measure the degree of perfection of a circle shape shows that there is no significant difference between fine and coarse grain size on circularity. This may be related to the ratio Do/d. The size of the specimen diameter is not small enough to give different deformation circularity.

Acknowledgment
The authors gratefully acknowledge the support of the LPDP from Indonesian Government for this Research with contract number: PRJ - 267/LPDP/2013.

References
