Surface Topography on Miniaturization of A Thin Circular Cylinder By An Impact Loading

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Abstract

Dimensional accuracy is one of the major problems when it produces small metal components. Surface topography significantly influenced the product surface dimension accuracy and the product surface quality. A series of circular specimens was tested; in order to understand the surface topography characteristics on a thin circular cylinder miniaturization which is given an impact loads on a lubricated condition. The specimen diameter was varied start from 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm with a fixed thickness of 0.5 mm. To get an average grain size, before the impact test process, all specimens were heated till 350° C for about 30 minutes. A drop weight test were performed where the specimen and the impact machine hammer was lubricated with oil. The same impact energy per area is given to the specimen by adjusting the load elevation. The surface topography after the impact test was observed with an optical microscopy and analyzed under SEM. It is found that the specimen surface topography result after the impact test process using oil as lubricant was different between the outer region and the inner region which is following the lubricant pocket model. The inner region area is characterized by a close lubricant pocket model with a surface seen as an orange peel mark. The outer region area is characterized by a smooth surface due to a direct interaction between the specimen surface and the suppressor surface. So, it is seen that giving a lubricant on the impact test would result two effects on the impact loading conditions. Second, for the oil at the inside or at the IR has negative effect by giving rough surface due to orange peel mark. The real contact area (RCA) fraction has increased by miniaturization seen from the ratio value between the outer region and the Inner region increased. From the SEM observations it is also seen that the surface
roughness increases with the specimen diameter increased. It is also found that the specimen has a more resistant to fracture by miniaturization.

**Keyword:** miniaturization, surface topography, outer/inner region, real contact area, orange peel mark.

**Introduction**
Small parts manufacturing industry is one of the large-scale industries with a high production rate. The need of making mini product with a high rate is one of the main reasons to choose metal forming as the manufacturing process. Metal forming techniques in this case is known as the micro-forming. It is well known that one of the methods that support the fabrication of high production rate in metal forming is drop forging process or hammer forging process. This is due to the use of high strain rate on the process. The high strain rate is obtained by providing impact loads.

The problem relating to components manufacture on micro-scale process is the product shape accuracy, product dimension and also the product surface quality. The accuracy level is far different from the macro-forming process. The small part product geometric tolerance is in a micron size range [1]. The surface quality level is in a contrast to large-sized products. Several studies related to the lubrication phenomenon, friction on surface topography for micro-forming applications has also been carried out. Bin et al [2] examines the specimen tribological size effect behavior on the cylinder with an upsetting test. The research was carried out for a dry condition and by using castor oil as a wet lubrication condition. The result shows that the size effect does not occur in the dry lubrication conditions because the friction factor is relatively constant.

However, the castor oil lubrication condition shows the size effect phenomenon. The friction factor increases collateral with the specimen diameter reduction [2]. The stamping process study was performed by Penget al [3]. The friction behavior on two different interfaces was studied, using a rigid and soft-punch. The result shows that the stress is equally distributed at the interface between specimens and soft-punch, when friction coefficient increases. In contrary at the interface between the specimen and the rigid-punch, the stress does not have an equal distribution as the friction coefficient increases. It was also noticed that deformation area is divided into a deformed area and un-deformed area.

The sheet material friction behavior using stretching test was conducted by vollersten et al [4]. The research result shows that on the miniaturization process, the friction increases and a large deviation occurs on the compressive force. However, extending lubrication does not give a significant effect on micro deep drawing process. This result was similar with the research conducted by Shuaib [5] who investigating the lubrication influence and friction effects on the CuZn30 foil thin sheet formability under a two different grain size and three lubrication condition variation. The result found that there is no significant effect on deformation force for different lubricants under a same grain size.
A Study conducted by Parazis et al [6], observing the shear deformation behavior by analyzing the micro-hardness characteristics on a micro-extrusion process under a no-lubrication condition. The research result is that the surface hardness increase for large grain size, compared with the small grain size. The surface deformation becomes significant for large grain size due to large shear deformation. Large shear deformation occurs as a result of large frictional effects. Another study conducted by Vollersten et al [7] about the size effect on the micro-metal components fabrication. The best approach relating to the friction phenomenon condition on a miniaturization scale is the lubricant pocket model.

Yao et al [8] investigated the formation of meso / micro tribological aspects by working out a high-frequency vibration on an upsetting process. The surface quality increases due to the friction decrease at the interface between the specimen and the suppressor. This is an indication that the flow deformation increased as a result of a high-frequency vibration. By applying high frequency vibrations, a friction reduction occurs. Deng et al [9] investigated the circular specimen surface deformation behavior by an upsetting test. The research result shows that there was an increase in friction at the interface between the specimen and the pressure die when the specimen dimensions decreases. It is also found that the real contact area is concentrated on the outer surface area and closed lubricant pockets are concentrated at the specimen inside surface.

Chan, et al [10] studied the size effect on micro plastic deformation and friction phenomena that occurs in the micro-cylinder compression test. The research result says that there is an increase in the open pocket lubricant fraction area followed by a decreasing specimen size. The research result also shows that local asperities increase under a miniaturization. Although the research on the surface characteristic have been carried out in the miniaturization but the lubrication effect in the impact load conditions still need a clearer understanding. In this paper, the lubrication effect in miniaturization under an impact load is investigated through a surface topography evaluation.

Material And Methods
The test material used is aluminum with a 98.9% aluminum content. The specimen size and shape is shown in figure 1. The deformation behavior due to the lubrication effect size would be observed experimentally. The impact test tool is using a drop weight test as shown in Figure 2. The weight given load is 5 kg. The tests were conducted under a lubrication condition. The test material used in this study is a 12 mm diameter aluminum cylinder. The specimen is pulled up to an extension by 5%, and then annealed at 350°C for about 30 minutes. Figure 3 shows the average grain size after annealed. The machining processes carried out on specimens prepared for a varying diameter of (Do)= 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm and a thickness of 0.5 mm. Each specimen gets the same impact energy per area. The surface topography due to impact loads would then be observed using optical microscopy and SEM.
**Figure 1:** Specimen size and shape.

**Figure 2:** Drop tower installation test.

**Figure 3:** Average grain size after heat treatment (110.8 μm).
Results And Discussion

Figure 4 shows the specimen before and after an impact loading with various initial specimen diameters. As shown in figure 4, the specimen diameter after impact was expanded. During impact loading, the specimen diameter was increase and the specimen thickness reduces. It is also seen that there is a different surface topography between the specimen outer surface region and the specimen inner surface region. From figure 4 it is also found that by reducing the specimen diameter, the outer region (OR) and the inner region (IR) ratio was increase. The ORis characterized with smoother surface than the IRas shown also in Figure 5.

![Figure 4: Specimen before and after impact loading.](image)

(a) Surface topography of outer region
(b) Surface topography of inner region

Figure 5: OR and IR Surface topography after an impact loading: (a) $D_o=7$ mm and, (b) $D_o=2$ mm.

Figure 6 shows the outer region and the inner region SEM image which were very different on the specimen surface roughness. The surface topography at the inner region was similar to orange peel mark.
Figure 6: SEM Topography of $D_o=2\text{mm}$ specimen: (a) for IR and, (b) for OR

Figure 7 shows the SEM surface topography of the specimen inner region for various $D_o$. It is shown that under a same impact energy per unit area, the surface topography roughness of was increased following the specimen initial diameter increase.

Figure 7: SEM Surface topography at the specimen inner region for various initial diameters; a. $D_o=2\text{mm}$, b. $D_o=3\text{mm}$, c. $D_o=4\text{mm}$, d. $D_o=5\text{mm}$, e. $D_o=6\text{mm}$, f. $D_o=7\text{mm}$. 
It is observed that by decreasing the specimen diameter, the specimen resist to fracture as shown in Figure 8. There are two kind of crack resulted from the experiment, the crack at the outer region and the crack at the inner region. Figure 9 shows the inner crack SEM morphology as a result of impact loading. It is shown that the number and the crack size at the inner region increase followed by the specimen diameter increase of specimen diameter as also shown in Figure 7.

As shown in figure 4 and 5 that there are the difference of surface topography between outer region and inner region. According to lubrication pocket model, there are two different lubrication phenomena for the circular specimen under compression loading[9]. The open lubricant pocket (OLP) was concentrating at the outer region and the close lubricant pocket (CLP) was at the inner region. It is well known that the surface of specimen consist of a lot of asperities area in micro scale as a result of previous process. These asperities filled with lubricant trapped during deformation create CLP. However asperities those are not filled with lubricant create OLP.
Figure 10: Specimen and tool cross section, with an open and close lubricant pocket illustration.

Figure 10 shows the illustration of the specimen and tool cross section that has a close and open lubricant pocket. The outer region is characterized by a smooth surface due to a direct interaction between the specimen and the die surfaces and creates a real contact area. The real contact area is the contact area between the tool and specimen without a lubricant interface [9].

The smoother the area on the outside (figure 5 and 6) is due to the lubricant running out and as a result of the specimen OR deforms by a direct contact between the specimen and die surface. It can be stated that the smoother surface that occurs in the specimen OR surface is a result of the direct contact between the specimen and the die which has a smoother and harder surface.

On the other hand, during the impact loading the IR also deforms but some of the lubricant was still trapped inside the CLP. The CLP deforms but with the lubricant still trapped in the asperities, resulting a specimen deformation as a mark on the surface left by the lubricant which is seen as an orange peel mark. As a result there is different surface quality between OR and IR. Figure 11 shows that under an impact loading condition, some of the lubricant is still left behind on the surface after impact. Impact loading is characterized by a high or a fast deformation. By increasing specimen diameter, the lubricant trapped in the contact area has not enough time to escape or running out. It can be explained that at a larger surface area, the lubricant numbers that is involve in the deformation process is larger and the CLP number at the specimen surface increases. The specimen surface and the die surface were separated by a lot of lubricant that being trapped at the close pocket area. Under a rapid loading, the lubricant was squeezed out and creates an orange peel pattern on the specimen surface (see Figure 6 and 7).

It can be conclude that lubricant attachment would result two effects under an impact loading condition. First, for the oil given on the outer region affected a positive result, giving better and smoother surface. Second, for the oil at the inner region has negative effect by resulting a rough surface.
The surface topography roughness tends to decrease by reducing initial diameter of the specimen (see Figure 7 and 8). This is caused by the increase of the open pocket fraction when the specimen diameter is reduced. Consequently, the real contact area (RCA) also increased. When the specimen diameter reduces, the inner grain ratio increases. This means that the deformation was dominated by the surface grain. Chan et al [10] pointed out that the grain number that involve in the surface deformation, affect the surface roughness. Chan also states that the surface grain flow stress is lower than the inner grain. Furthermore, the deformation by surface grain is different with inner grain. The surface grain deformation is characterized by the shear deformation due to the contact with the die surface. When the specimen diameter was reduced, the surface grains with a low flow stress were dominant in controlling the deformation by a shear deformation and as a result the RCA increases. Also, by decreasing diameter, it would accommodate more lubricant escaping and creating RCA.

The other reason is that the deformation speed may be attributed with the specimen radial direction. It is known that in order to work out equal impact energy to a large diameter specimen or a small diameter specimen then the impact dropped height could be different.

Figure 11: Effect of a lubrication under an impact loading; (a) before lubrication, (b) after lubrication and before impact, (c,d) after impact.
The radial deformation velocity for a large specimen diameter is higher due to a higher impact velocity. The relationship between the impact velocity and the radial velocity for a rapid compression on a circular cylinder could be defined as follows: [11].

\[ u = \frac{r \cdot V}{2t} \]  

Where \( u \) is the specimen radial velocity, \( r \) is the specimen radius, \( t \) is the specimen thickness and \( V \) is the dropped weight impact velocity. The relationship between the impact velocity (\( V \)) and impact distance (\( h \)) is given as follows:

\[ V = (2gh)^{1/2} \]  

**Figure 12:** Circular Cylinder specimen diameter vs Radial velocity for rapid compression.

From figure 12 it is seen that the relation between the specimen diameter and the radial velocity based on equation 1. The radial velocity increases with the specimen diameter increases. On the impact loading, the radial velocity increases with the dropped weight elevation, and followed by increase deformation rate. The specimen deformation rate is high. It can be concluded that the surface roughness increase is due to the combination of a high radial direction deformation rate and the close lubricant pocket (CLP) condition.

It is also seen that there is no crack detected for the smallest specimen diameter. The crack is detected in a larger diameter. Crack at the outer region can be related to the circumferential and radial stress. However, the crack at the inner region is also due to the high hydrostatic lubricant pressure contribution at the close lubricant pocket (figure 9). The combination of sharp asperities and hydrostatic pressure creates a stress concentration at the edge of asperities (figure 13). This condition produces a high stress concentration at the sharp asperities that would cause fracture. Another reason could be attributed to the specimen surface area to the specimen volume ratio. The impact loads is a dynamic load. Fracture toughness due to dynamic loads is different from quasi-static loading. It is influenced by the specimen volume [12]. In materials that undergo dynamic load, fracture toughness is affected by \( A/V \) [12]. The other reason is, when \( A/V \) decreases, the deformation follows the characteristic of
bulk deformation. When A/V increases, the deformation tends to be close to the sheet deformation. In this case, specimens have failed due to friction.

![Lubrication pressure illustration due to impact loading and stress concentration at the asperity.](image)

**Figure 13:** Lubrication pressure illustration due to impact loading and stress concentration at the asperity.

**Conclusion**

It can be concluded that the effects of lubrication on aluminum surface topography under an impact load as follows:

- Under an impact load, outer region has a smooth surface due to the lubricant escaping and the increase of OPL fraction area which is creating a real contact area between the specimen and the hammer tool. The inner region has a rougher surface resembles an orange peel marks. The outer region has a smoother surface due to a direct contact.
- Reducing the diameter of the specimen causes the ratio between the outer region and the inner region increased or in other words OPL fraction increased in small specimen diameter.
- By increasing the specimen diameter, the specimen surface roughness increases. Because the contact surface area increases so the number of CPL also increased. Increased surface roughness of the specimen diameter due to the high deformation in the radial direction.
- Crack in the inner region is caused by a radial stress and circular stress combination, high-pressure lubrication and sharp asperities geometry. The effect of this combination makes the high stress concentration at the edge of the asperities. The specimens are more resistant to cracking with miniaturization.

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