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Araştırma Makalesi / Research Article

Examination of Deformation in Thin-Walled Structures Processed by Micro-Milling Method

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ABSTRACT: Micro-thin-walled structures are frequently encountered in micro-pumps, micro-channel cooler plates, and micro-molds in the defense, aerospace and biomedical sectors. One of the micro-machining methods frequently used to obtain micro-thin-walled structures is micro-milling. The micro-milling method makes machining possible for micro-components with high accuracy and a good surface finish. However, there are many issues to consider when micro-milling thin-walled geometries. The fact that the wall deformation is directly related to the rate of progression necessitates knowing what effects the rate of progression cause on the wall deformation. Because the micro milling technique is generally used as the final cutting process in the creation of thin wall geometries in the industry. In this study, thin-walled structures were obtained by micro-milling the Al6061-T6 material. The influence of feed rate on wall deformation was investigated by applying different feed rates in micro milling experiments. Wall deformation measurements were performed using a motorized optical profilometer device. It has been observed that increasing feed value causes an enhance in cutting forces, it also causes an increase in the deformation of the micro-thin wall. The deformation distance between the end points of the micro-milled wall geometry using a feed rate of 1 µm/tooth is three times greater than the thin-wall geometry created using a feed rate of 0.2 µm/tooth. It has been determined that the deformation is much higher in the entrance and exit areas of the micro-thin wall. The wall deformation also decreases from the upper point to the lower points of the micro-thin wall. While the deviation distance in the measurement taken from the upper point of the wall geometry obtained by using the 1 µm/tooth feed rate, where the deformation is more, can reach 100 µm, the deviation at the lower point of the wall is negligible.

Keywords: Thin Wall Structures, Micro Milling, Plastic Deformation, Cutting Parameters, Al6061-T6.

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1. INTRODUCTION

The need for micro equipment is increasing day by day with the development of technology. Thin-walled structures are frequently encountered in micron-sized equipment and frequently used in aerospace, space technologies and biomedical applications. Examples of these structures are micro-channel cooler plates, micro propellers, micro molds, micro pumps, biodegradable implants (Yi et al., 2019). Due to the geometrical properties of these micro-scale equipment, they have to be produced very precisely. Micro milling is a widely used micro machining method for the creation of thin wall geometries (Dornfeld et al., 2006; Fabio et al., 2017). The biggest problems encountered in micro-milling of thin-walled structures are plastic deformation and dimensional errors in the wall geometry (Lazoğlu and Mamedov, 2016). The result is a poor surface quality with machining defects. For this reason, cutting parameters and cutting strategy must be carefully chosen in order to minimize wall deformation during micro-milling of thin-walled structures.

For a structure to be defined as a thin wall, the ratio of the wall height (h) to the wall thickness (t) must be greater than 10 (Khandagale et al., 2018). It is stated that the wall thickness should be 100 µm or less in order to dimensionally separate the thin walls produced by the micro-milling method from the thin walls produced by the conventional milling method (Figure 1) (Yarin et al., 2009).

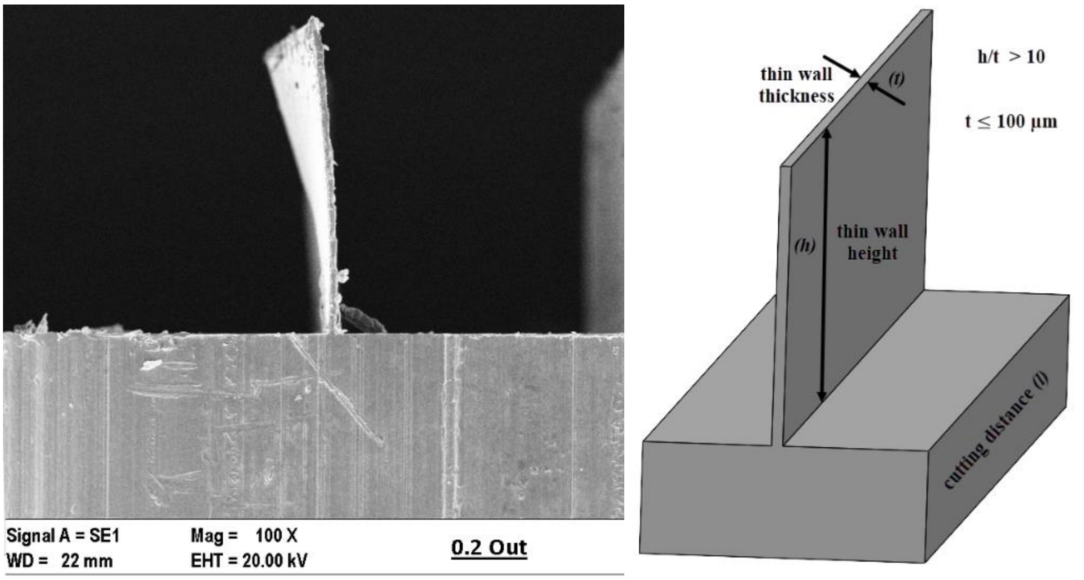


Figure 1. SEM image of a sample microthin wall and description of the structural dimensions of the wall

The most important factors to consider in micro machining is the size effect (Hasçelik and Aslantaş, 2021). The size effect is directly related to the minimum chip thickness. As the size gets smaller, different effects are observed depending on the minimum chip thickness (Aslantaş et al.,2020; Chae et al., 2006). In order to eliminate these effects, it is important to define the minimum chip thickness. For a healthy micro milling process, the cutting parameters should be selected depending on the minimum chip thickness (Aslantaş and Çiçek, 2018). Choosing the optimum cutting parameters is one of the main factors in order to minimize the part deformation (Erçetin et al., 2020; Aslantaş and Alatrushi, 2021). High cutting forces in micro milling, vibrations due to size effect and negative rake angle due to minimum chip thickness cause instabilities in the cutting process (Shimada et al., 1993; Yuan et al., 1996; Kim et al., 2002; Chae et al., 2006; Sun and Cheng, 2010). For this reason, in the micro milling process, the cutting process should be completed by taking into account the effects of all these issues.

Thin-walled microstructures used in industry are generally made of titanium and aluminum material blocks (Ciecielag and Zaleski, 2022). Aluminum alloys are frequently preferred in the industry due to their thermal and electrical conductivity, being suitable for heat treatments, being easily shaped, being light, having low yield stress and high fatigue resistance (Akram et al., 2018). Its low rigidity, on the other hand, is a major disadvantage, especially in the processing of thin-walled structures. Al6061 alloy stands out as the most versatile heat treatable alloy of aluminum. With the T6 heat treatment, the aluminum alloy reached its maximum precipitation hardening. For this reason, yield strength (>240 MPa) and tensile strength (>290 MPa) are quite high (Akram et al., 2018).

Deformation errors are a common problem in micro-milling of thin-walled structures (Gao et. al, 2022). Researchers have done many studies to reduce wall deformation. Ramanaiah et al., (2017) drew attention to optimum cutting parameters to minimize deformation. They proved that the wall deformation is low at high cutting speed, low depth of cut and feed rate (Gao et al., 2022). With the milling direction and strategy, the wall deformation can be reduced to even lower values (Li et al., 2010). Cheng et al., (2018) correlated the tool edge radius with the minimum chip thickness in determining the feed rate in thin-walled structures formed by micro milling. As a result, they stated that the minimum chip thickness is not only a fixed ratio of the tool edge radius, but also the depth of cut should be taken into account. Li et al., (2018) modeled wall deformation in the micro milling process with the finite element method. Loehe et al., (2012) used optical measuring instruments to measure the mechanical deformation value of micro thin-walled workpieces. Gao et al., (2016) developed a strategy to reduce thin-wall deformation with optimum cutting parameters and reduced the wall deformation by 52%.

In this study, the deformation of thin-walled structures obtained by micro-milling method from Al6061-T6 alloy, which is frequently used in the aerospace, defense and biomedical sectors, was investigated. The effects of feed rate on cutting forces and wall deformation were observed. In addition, it is graphically shown how the wall deformation changes from the top of the thin wall to the bottom of the wall. Thin wall deformation measurements were taken using a different measurement technique than the studies in the literature. In addition, the effect on the wall deformation was determined by using two different feed rates lower and higher than the minimum chip thickness. The coming out results and possible causes are explained. Thus, the efforts to increase the quality of the parts aims to find a response in industrial applications.

2. MATERIALS AND METHODS

2.1 Experimental Setup

In the study, a special horizontally positioned experimental setup was used for micro milling experiments (Figure 2). The speed adjustment of the IMT brand spindle, which can go up to 60000 rpm, and the axis movements supported by micro stepper motors can be controlled with the help of a computer. Compressed air obtained from the compressor was used to fix the cutting tool to the spindle with the help of pliers. The cutting tool moves along the Z axis. Thus, the depth of cut is given by the Z axis. The sample holder, on which the workpiece is fixed, is located on the mini dynamometer (Kistler-9119AA1) fixed to the slides moving along the X axis. During the cutting process, the force data measured by the dynamometer is graphically printed on the computer screen with the help of the amplifier. During the cutting process, the feed is on the Y axis. A Usb microscope was utilized to observe the wall geometry during cutting.

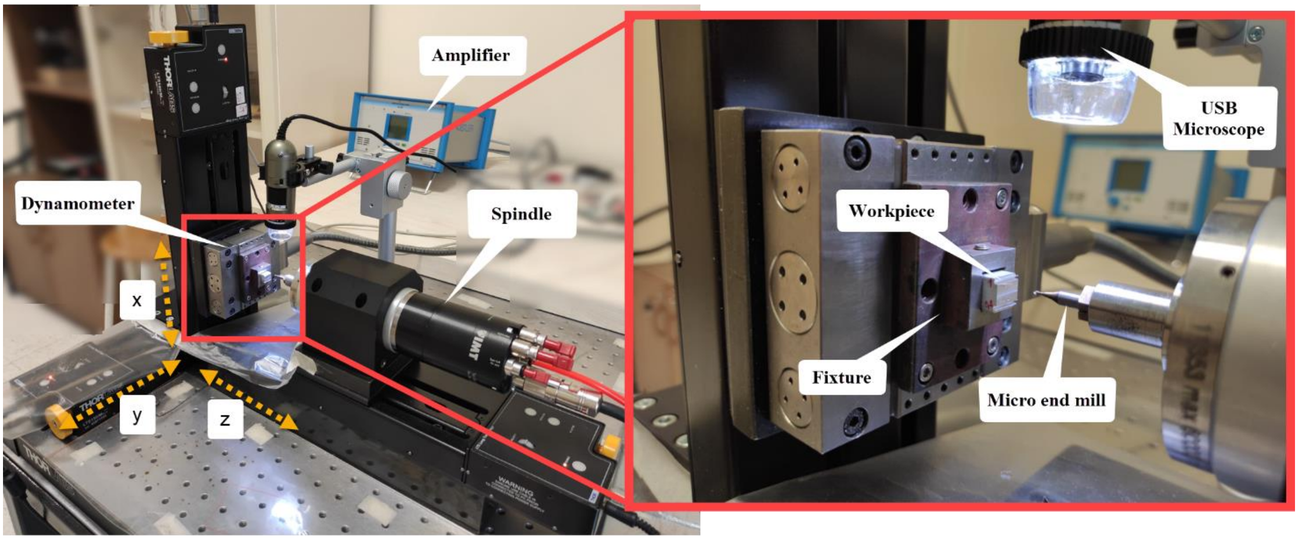


Figure 2. Experimental setup used in the study

2.2 Material and Cutting Tool

In the study, Al6061-T6 alloy, which has a widespread production volume in terms of its mechanical properties (Table 1), was used (Akram et al., 2018). Supplied with dimensions of 10 mm x 10 mm x 3000 mm, the Al6061-T6 workpiece was cut into small pieces using a precision sample cutting device. After fixing the 10 mm x 10 mm x 20 mm workpiece to the sample holder, it was subjected to micro milling to obtain a thin wall structure (Figure 3).

Table 1. Mechanical properties of Al6061-T6 material (Warsi et. al., 2017)

Material	Density (g/cm^3)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Young's modulus (GPa)	Thermal conductivity (W/m K)
Al 6061-T6	2.7	310	275	69	167

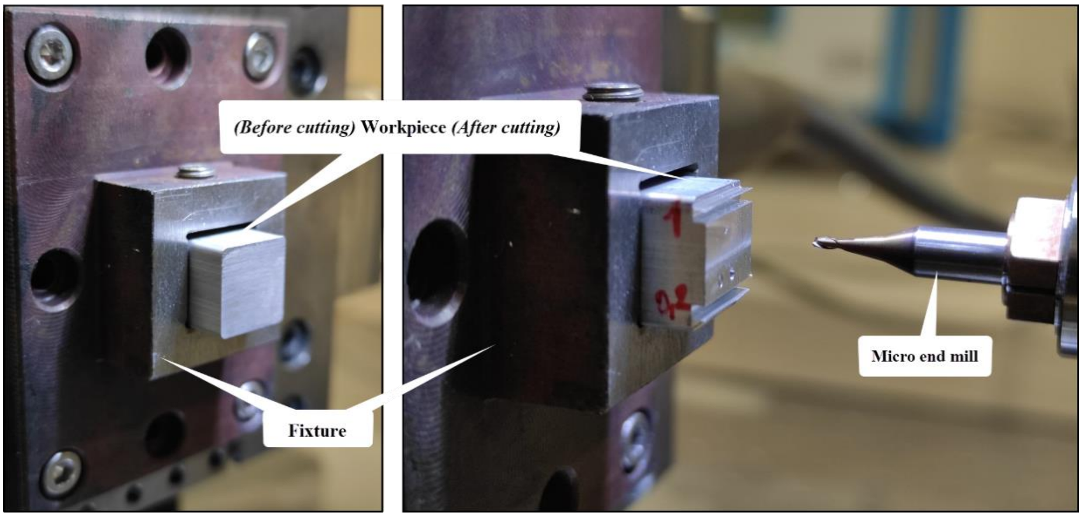
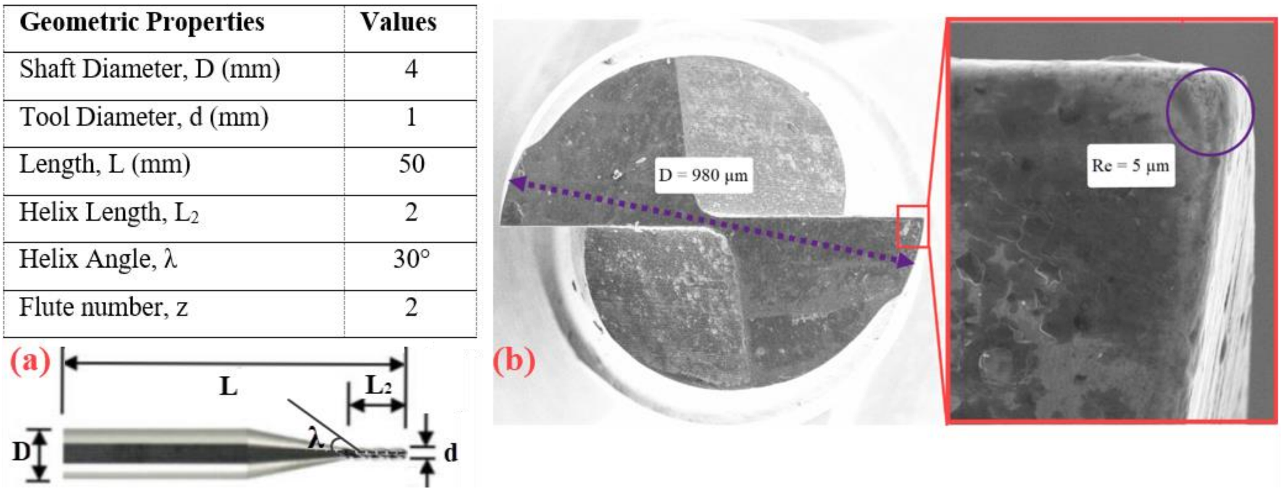


Figure 3. View of the workpiece before and after cutting

In the micro-milling of the thin wall structure, a Tungsten Carbide cutting tool with 1 µm AlTiSiN coating was used in the geometric properties in Figure 4a. Although the tool diameter is specified as 1 mm according to the data of the company from which the cutting tool is supplied, Predicting that the diameter differences in micron size may affect the wall thickness, the cutting tool diameter was measured using an electron microscope (SEM) before starting the cutting experiments (Figure 4b). The diameter value of the cutting tool used in these experiments was 980 µm, and the edge radius was 5 µm.



Geometric Properties	Values
Shaft Diameter, D (mm)	4
Tool Diameter, d (mm)	1
Length, L (mm)	50
Helix Length, L_2	2
Helix Angle, λ	30°
Flute number, z	2

Figure 4. Geometric parameters (a) and SEM photographs (b) of the cutting tool used in cutting experiments

2.3 Experimental Systematics

At first, constant cutting speed Vc = 94.1 m/min, speed N=30000 rpm and ap=0.1 mm depth of cut at 7 different feed rates (0.025, 0.5, 0.1, 0.2, 0.5, 1, 2 µm/tooth) micro milling experiments were carried out to confirm the effect of feed rate on cutting forces. Next, a thin wall structure was formed separately by micro milling for 0.2 µm/tooth and 1 µm/tooth feed rates. These feed rates were selected among the parameters recommended by the tool manufacturer. It is aimed to compare the effect of cutting forces and ploughing by selecting values below and above the minimum chip thickness. The milling technique used to create the thin wall is shown in Figure 5a. A wall height of 1 mm was obtained by performing a total of 20 unloading operations from both sides of the wall, respectively, ap = 0.1 mm (Figure 5b). After the first unloading process from left to right, the cutting tool was shifted by 1030 µm considering 980 µm tool diameter + 50 µm wall thickness, and the unloading process was performed from right to left. This process was repeated 10 times, giving 0.1 µm more cutting depth each time. The geometric dimensions of the thin wall structure at the end of the cutting process are shown in Figure 5c. At the end of the cutting process, the wall thickness was measured as 40 µm. The 10 µm difference is thought to be due to the run out of micro-milling process. In this case, the ratio of the wall height to the wall thickness (h/t) is 25. In Figure 5d, a photograph of the thin wall structure taken with a Usb microscope at the end of the micro-cutting experiment is shown.

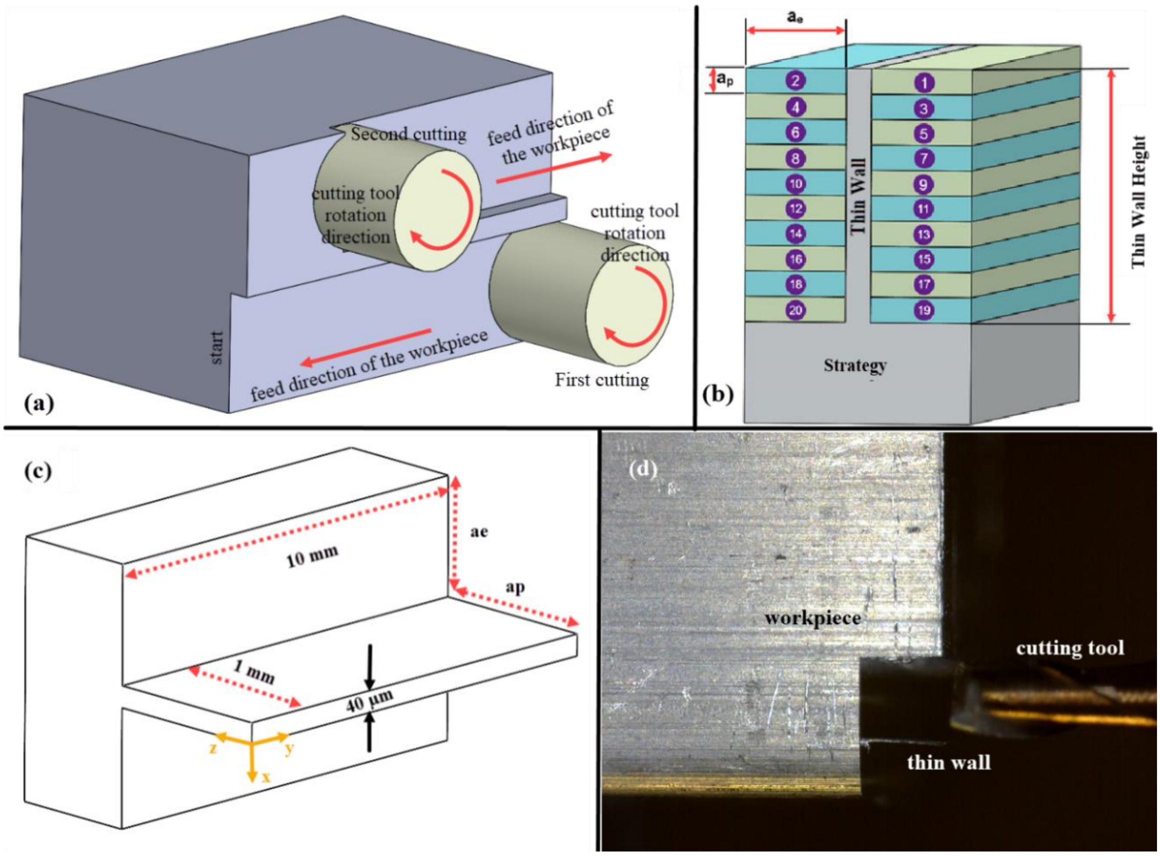


Figure 5. a) The milling technique used in the creation of the thin wall b) The strategy applied in the creation of the thin wall c) The geometric dimensions of the thin wall d) The photograph of the thin wall taken with a Usb microscope

2.4 Measurement of Thin Wall Deformation

Deformations of thin-wall structures formed at two different feed rates by micro-milling method were measured using an optical profilometer (Figure 6). Measurements were taken from the wall surface and compared with the Nanovea brand device working with white light technology. The scanning distance was along the wall (10 mm), the scanning frequency was 1000 Hz, the step was 0.1 µm.

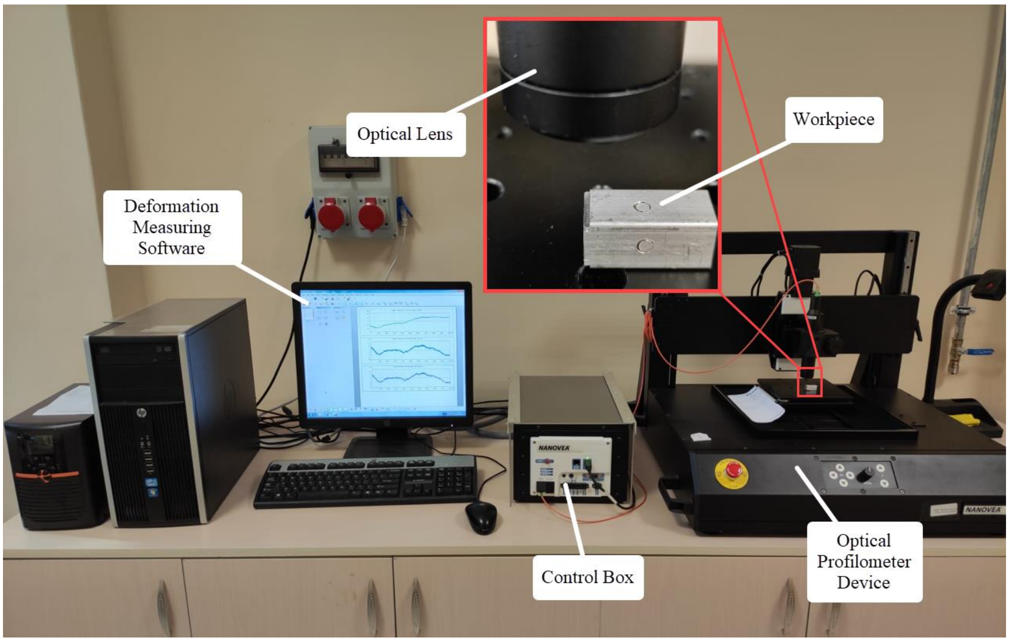


Figure 6. Optical profilometer device used in thin-wall deformation measurements

First, the laser beam in the optical lens is focused on the workpiece. Then, zeroing process was performed in the y and z coordinates from the top surface of the thin wall and to the exit point of the cutting part. The first scanning was performed along the lateral surface of the wall (10 mm) in the y-axis after the optical focus was shifted 0.05 mm from the 0 point of the wall in the +z direction. Subsequently, a total of 6 scans were made by moving 0.15 mm more in the +z direction before each scan (Figure 7). This measurement was repeated in the same way for thin-wall structures formed with 0.2 µm/tooth and 1 µm/tooth feed rates, separately.

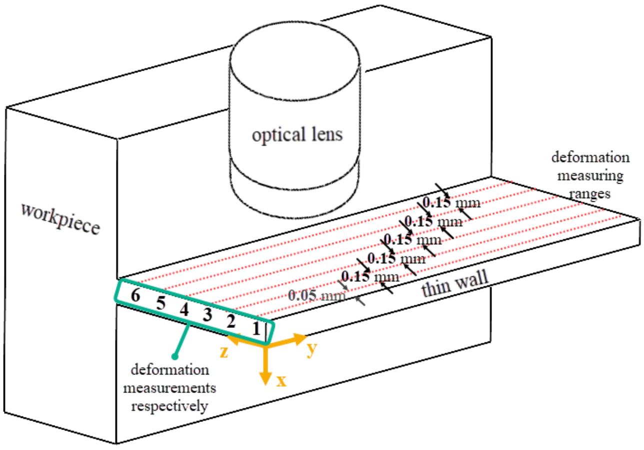


Figure 7. Thin wall deformation measuring mechanism

3. RESULTS AND DISCUSSION

3.1 Comparison of Cutting Forces

In order to observe thoroughly the effect of feed rate on cutting forces, micro-milling experiments were carried out at constant depth of cut and cutting speed. Seven different feed rates were used to determine exactly whether the cutting was performed by sliding or ploughing mechanism. The amount remaining between the maximum and minimum force values was taken into account in the cutting force data obtained graphically in the computer environment. This amplitude value, which is widely used in micro milling tests, is also called Peak to Valley (Aslantaş et al., 2022). It is not always possible to define the minimum chip thickness by examining the Peak to Valley values that change depending on the feed rate (Aslantaş et al., 2022). In the literature, it is stated that the minimum chip thickness is between 20% and 30% of the cutting edge radius (Cheng and Huo, 2013). While this rate is 30% in titanium alloys (Aslantas et al., 2020), it can go up to 40% in aluminum alloys (Chen et al., 2020). In another study, it was defined that the minimum chip thickness was 17% of the edge radius (Wu et al., 2020). In this study, the minimum chip thickness is thought to be between 0.5 µm and 1 µm. Since the edge radius is 5 µm, the minimum chip thickness corresponds to approximately 15% of the edge radius. Since the ploughing mechanism is effective at low feed rates (0.025, 0.05, 0.1 µm/tooth), it is observed that there is an instability in the Fx and Fy forces as the feed rate increases (Figure 8). The reason for this situation can be explained by the size effect in the micro milling process. Cutting forces exhibit an unstable behavior at feeds per tooth close to or below the minimum chip thickness. To eliminate the effect of ploughing, at higher feed rates (0.2, 0.5, 1, 2 µm/tooth), it is seen that the cutting forces increase linearly as the feed rate increases (Figure 8). This is explained by the fact that the sliding mechanism is effective, as the minimum chip thickness is increased to higher feed per tooth, similar to the conventional milling process.

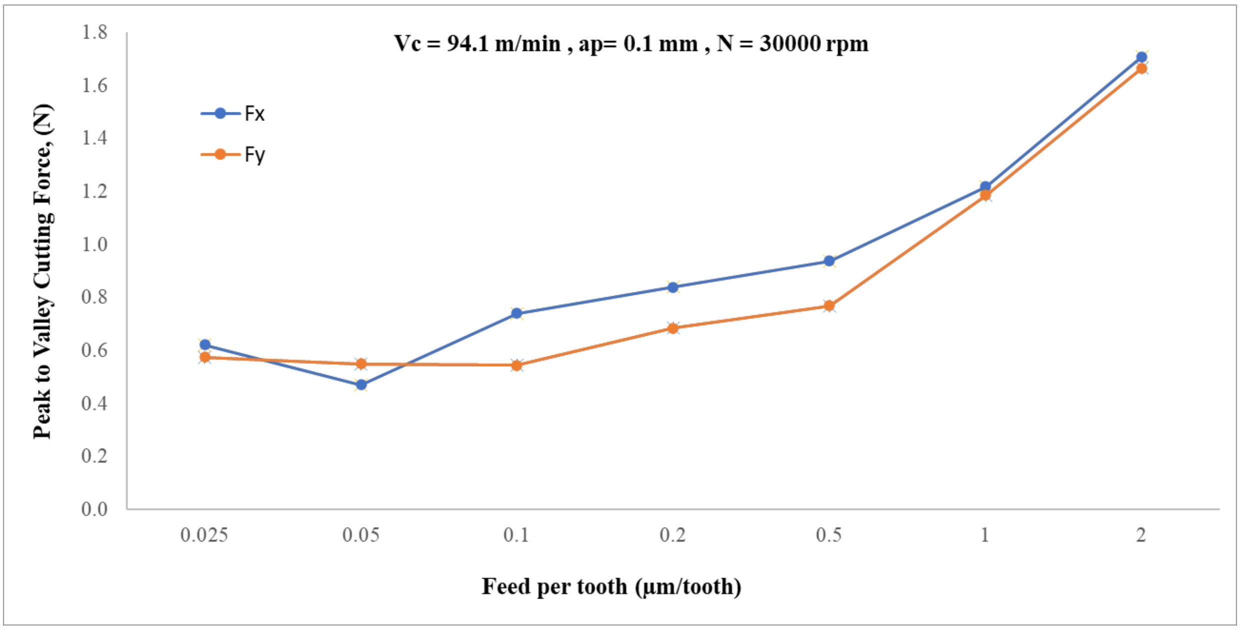


Figure 8. Cutting forces according to different feed rates

3.2 Thin Wall Structure Deformation

After obtaining thin wall geometry for two different feed rates with micro milling, deformation measurements were made on the wall surface using the technique in Figure 7. The measurements made separately from different heights for 0.2 μm/tooth and 1 μm/tooth feed rates are compared by graphing in Figure 9.

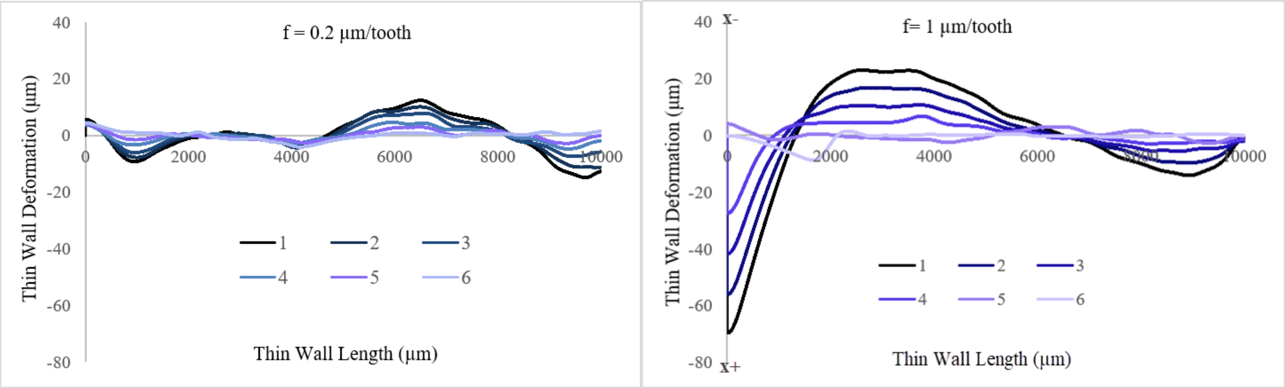


Figure 9. The change in thin-wall deformation from the upper surface of the wall to the lower surface for feed rates 0.2 μm/tooth and 1 μm/tooth

In Figure 9, it is seen that the wall deformation increases on the wall surface where the height is higher for both feed rates. The ratio of the wall height to the wall thickness decreases as one moves from the 1st measurement to the 6th measurement. Accordingly, the deformation in the lower part of the thin wall is quite small. Because the geometry is more rigid in the bottom of the wall.

Another striking point in Figure 9 is that the wall geometry micro-milled with a feed rate of 1 μm/tooth has been more deformation than the wall geometry obtained using a feed rate of 0.2 μm/tooth. At a feed rate of 1 μm/tooth, the deformation range between the end points of the workpiece is about 100 μm, while at a feed rate of 0.2 μm/tooth, the maximum deformation range is about 30 μm. This shows that there is a difference of more than three times. As the feed rate increases, the increase in cutting forces also increases the wall deformation. In this context, the results of cutting force and wall deformation confirm each other. Considering that the wall thickness is 40 µm, deviation in the x-axis to the wall thickness of approximately two and a half times in a thin-walled structure where the feed is 1 µm/teeth indicates that the cutting process was not performed under optimum conditions.

In order to observe the effect of feed on wall deformation more clearly, the number 1 measurements taken from the top / end point of the wall were compared for both feed rates (Figure 10). As stated in figure 9, it is clearly seen that the thin-wall deformation, which is subjected to micro-milling with a feed rate of 1 µm/tooth, is quite high compared to the workpiece with a feed rate of 0.2 µm/tooth. A better surface finish can be achieved at low feed rates, but minimum chip thickness should also be considered. Increasing wall deformation due to increased feed is much more dominant than deformation due to size effect.

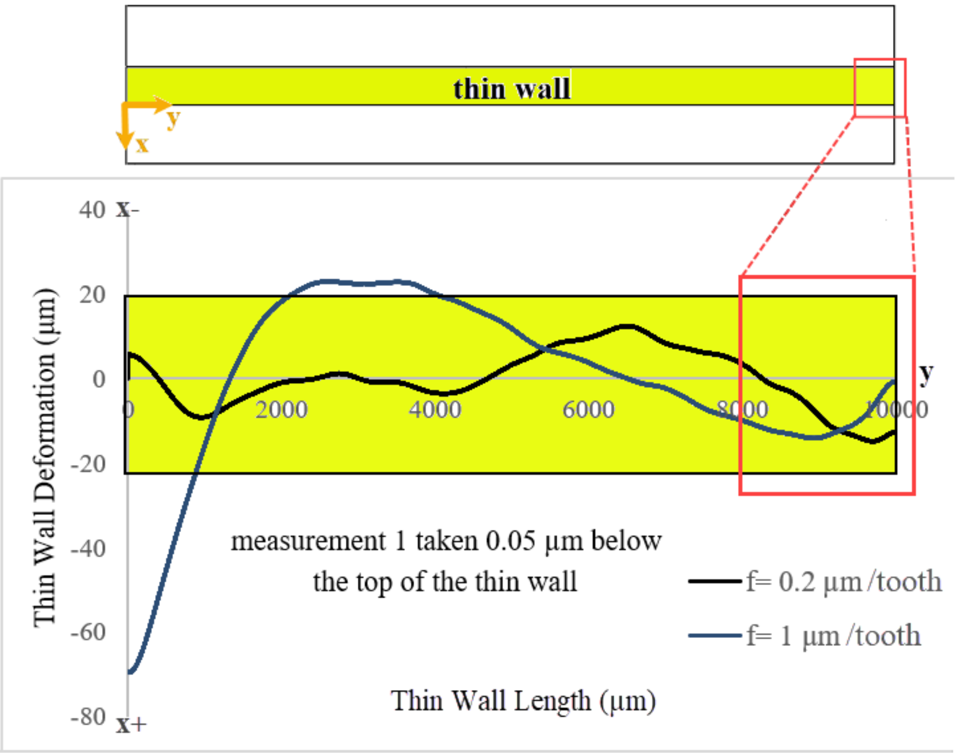


Figure 10. Comparison of wall deformation of thin-wall structures subjected to micro-milling at two different feed rates

In Figure 11, SEM images of these two thin wall geometries are given. SEM images were taken separately from the entrance and exit areas. In Figure 10, it is seen that the deformation measurement in the entrance area of the thin wall formed with 1 µm/tooth advance value is considerably higher than the thin wall obtained with 0.2 µm/tooth advance value. Looking at the SEM images in Figures 11a and 11b, this result is clearly observed. The deformation images in the exit area in Figure 11c and 11d are also parallel to the deformation measurements. In Figure 11e, 11f, 11g and 11h, the top view of the wall geometry is given for both feed values. The SEM images of the thin wall match exactly with the deformation measurements made from the wall surface, which proves the accuracy of the measurements made with the optical profilometer device.

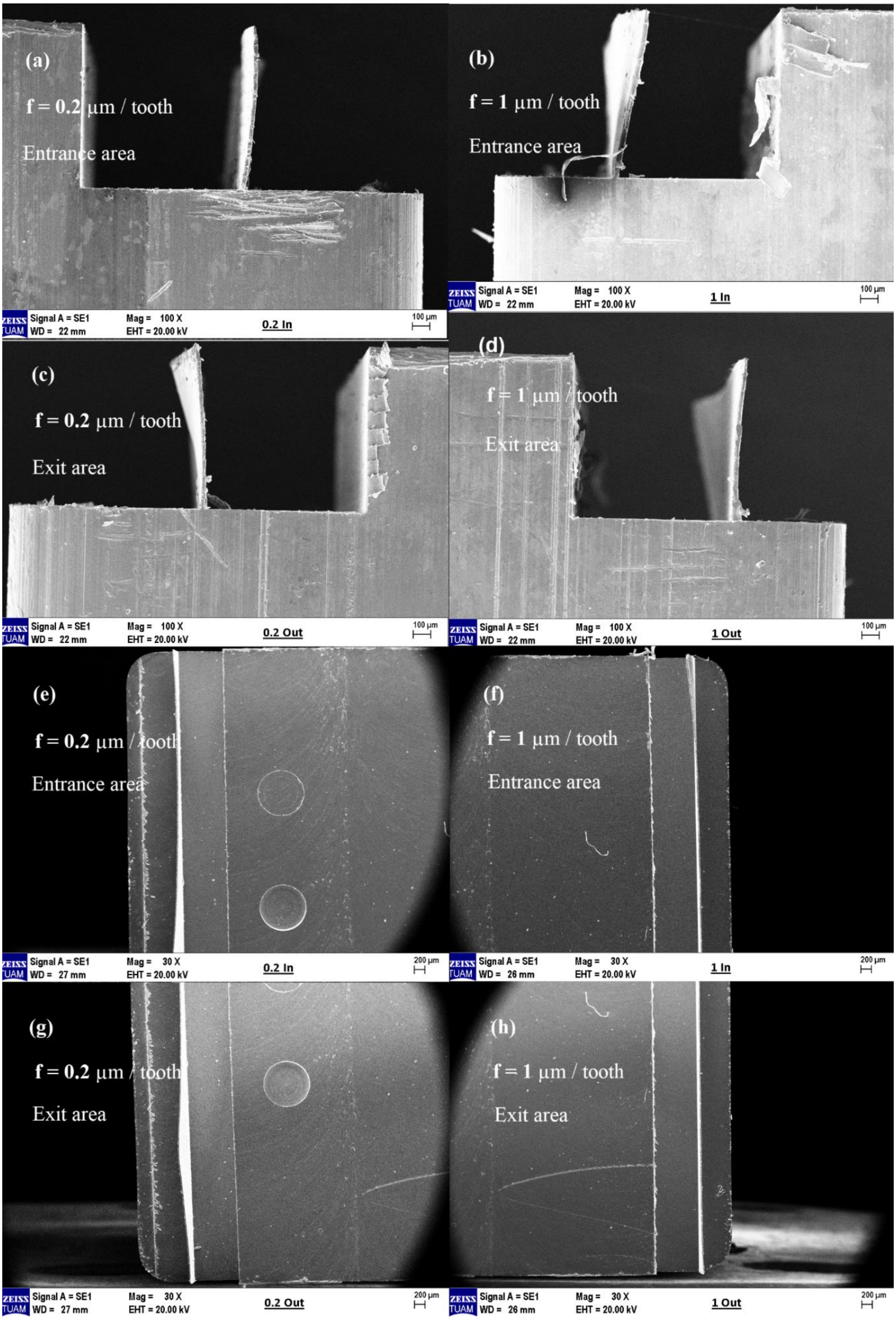


Figure 11. SEM images of the entrance and exit areas of thin-wall geometries created at 0.2 and 1 μm/tooth feed rates

In order to understand the cause of deformation in micro milling of thin-walled structures, it is necessary to examine the deformation mechanisms. Thin-walled structures are subject to bending as a result of plastic deformation under the influence of external elastic loadings during cutting (Yi et. al., 2019). As a result of bending, elongation occurs at certain points of the thin wall and shortening at other points. The increase in cutting forces in direct proportion to the increase in the feed rate also increases the deformation of the external loadings on the wall. It is seen that the workpiece is subjected to bending deformation at both feed rates. As it can be understood from the measurement results in Figure 9 and 10 and the SEM images in Figure 11, the bending deformation of the sample with a feed rate of 1 μm/tooth is higher than the bending deformation of 0.2 μm/tooth. This difference is clearly seen especially in the entrance area. As the feed rate increases, the bending deformation increases, and at much higher feed rates, fracture occurs with the increase in the loads to which the micro thin-walled structure is exposed (Xiang and Yi, 2021).

4. CONCLUSIONS

In this study, differences in wall deformations were investigated by creating thin wall structures by micro-milling using Al6061-T6 material. The wall deformations of the workpieces subjected to micro-cutting at two different feed rates were compared using different measurement techniques. The important findings of the study are as follows:

- It is seen that the cutting forces increase linearly with the increase of the feed rate, but at feed values per tooth become close to the minimum chip thickness, instabilities arise in the cutting forces because of the effective ploughing mechanism.
- When the deformation measurements on the thin wall surface are examined, the deformation at the top/end point of the wall is considerably higher than the deformation at the bottom point of the wall. The deformation decreases as you go from the upper point of the thin wall to the lower point.
- It was observed that the deformation in the entrance and exit parts of the thin wall was more than the other parts.
- When the feed rates are compared in terms of wall deformation. It was observed that the deformation of the thin wall structure obtained with 1 μm/tooth feed rate was about three times higher than the thin wall structure obtained with 0.2 μm/tooth feed rate. This shows that the deformation caused by the increase in cutting forces is more dominant than the deformation caused by ploughing.
- Cutting forces and thin-wall deformation results show that the surface quality deteriorates with increasing feed rate.

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6. CONFLICT OF INTEREST

Authors approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Ahmet Hasçelik and Kubilay Aslantaş determining the concept and design process of the research and research management, data analysis and interpretation of results, critical analysis of the intellectual content, preparation of the manuscript, and final approval and full responsibility. Besides Ahmet Hasçelik is contributed the data collection.

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