Mühendislik Bilimleri ve Tasarım Dergisi
8(2), 643 – 654, 2020
e-ISSN: 1308-6693

Journal of Engineering Sciences and Design
DOI: 10.21923/jesd.446078

Derleme Makalesi Review Article

THE BASIC CONCEPTS OF MICRO-MILLING PROCESS AND ITS REVIEW IN TERMS OF DISTINCTIVE PARAMETERS

Luqman Khaleel Haydery ALATRUSHI[1], Fevzi BEDIR[2], Nihat YILMAZ[3*]

[1] Suleyman Demirel University, Graduate School of Natural and Applied Sciences, Mech Eng., Isparta, Turkey
[2] Gebze Technical University, Faculty of Engineering, Department of Mech. Eng., Gebze, Turkey
[3] Isparta University of Applied Sciences, Faculty of Technology, Department of Mech. Eng., Isparta, Turkey

Keywords
Micro-Milling, Cutting Forces, Surface Roughness, Burr Formation.

Abstract
The micro-milling process is relating to the production of miniature parts, and it is one of the significant micromachining processes. The size of parts produced by micromachining is smaller than millimeters and in the range of a few microns. In the last years, the demand for needs to minimal parts in industries, such as biomedical, communication, and aerospace have been increased. To encounter this need, one of the proper solutions is the micro-milling process. In this study, a review of the micro-milling process was achieved in terms of the important common terms and some concepts. Terms like size effect, minimum chip thickness, and ploughing phenomenon were evaluated with respect to literature. These terms can be taken into account to distinguish a major difference between micro and macro cutting processes. In addition to, surface quality is an important required factor for machined parts. In this work also the surface roughness and burr formation mechanism were showed because they represent an inevitable result in the micro-cutting process. In addition to the micro-milling process have been assessed in terms of important factors used in determining the quality of workpieces such as surface quality, burr formation, and cutting forces. In conclusion, this study investigated the important parameters in the micro-milling process and provided general information to compare the micro-milling with conventional milling.

MİKRO FREZELEME İŞLEMİNİN TEMEL KONSEPTİ VE ÖZGÜN PARAMETRELER AÇISINDAN GENEL DEĞERLENDİRMESİ

Anahtar Kelimeler
Mikro Frezeleme, Kesme Kuvvetleri, Yüzey Pürüzlülüğü, Çapak Oluşumu.

Öz
Mikro frezeleme işlemi minyatür parçaların üretimi ile ilgilidir ve önemli mikro işleme proseslerinden biridir. Mikro işleme ile üretilen parçaların boyutları milimetreden daha küçük olup birkaç mikron mertebesindedir. Son yıllarda biyomedikal, iletişim ve havacılık gibi birçok endüstrilerde mini parçalara olan ihtiyaç artmıştır. Bu ihtiyacı karşılamak için en uygun çözümlerden biri mikro frezeleme prosesi ile üretim yöntemidir. Bu çalışmada, mikro frezeleme işlemi açısından öneme sahip yaygın terimler ve bazı kavramlar gözden geçirilmiştir. Boyut etkisi, minimum talaş kalınlığı ve kazınma fenomeni gibi terimler literatür ışığında incelenmiştir. Bu terimler, mikro ve makro kesme süreçleri arasındaki farkı göstermek için dikkate alınabilir. Çalışmada ayrıca işlenmiş parçaların kalitesini belirlemede kullanılan önemli faktörlerden; yüzey kalitesi, çapak oluşumu ve kesme kuvvetleri gibi parametreler açısından, mikro frezeleme işlemleri kritik edilmiştir. Sonuç olarak bu çalışma ile mikro frezeleme işlemindeki önemli parametreler incelenmiş ve mikro frezelemenin geleneksel frezeleme işlemiyle farkını ortaya koymak için genel bilgiler sunulmuştur.

Alıntı / Cite
Alatrushi, L.K.H., Bedir, F., Yılmaz, N., (2020). The Basic Concepts of Micro-Milling Process and Its Review in Terms of Distinctive Parameters, Journal of Engineering Sciences and Design, 8(2), 643-654.

* İlgili yazar / Corresponding author: nihatyilmaz@isparta.edu.tr, +90-246-214-6794

Yazar Kimliği / Author ID (ORCID Number)	Makale Süreci / Article Process	
L.K.H. Alatrushi, 0000-0001-6613-2848	**Başvuru Tarihi / Submission Date**	19.07.2018
F. Bedir, 0000-0002-9202-3458	**Revizyon Tarihi / Revision Date**	26.04.2020
N. Yılmaz, 0000-0002-8689-1048	**Kabul Tarihi / Accepted Date**	06.05.2020
	Yayım Tarihi / Published Date	25.06.2020

1. Introduction

In recent years, miniaturized components became a significant need in different industries such as electronics, biomedical, communication, and aerospace. The miniaturization in the micromachining process strongly will be enhanced the evolution in the technology and in a broad spectrum of producing components. The micromachining process requires reliable and frequent methods to achieve a high accuracy in the products. It has a higher production rate from the non-conventional manufacturing methods. In general, micromachining processes provide the products which have the range between a tens micrometer to a few millimeters in size. The definition of the micromachining process considers as one of a complex cutting process and many researches highlighted the specification of micromachining. Masuzawa and Tönshoff (1997) proposed if the undeformed chip thickness ranges from 0.1 to 200 μm, so the cutting is under the micro process. Masuzawa (2000) acknowledged also that the micromachining definition varies according to the viewpoint of person, machining method and type of product and material. Liu et al., (2004) said that when the undeformed chip thickness during the cutting process is comparable to the tool edge radius then the cutting process is micromachining. Chae et al., (2006) defined micromachining as a productive way of miniature components and devices with size varied from tens of microns to a few millimeters. Dornfeld et al., (2006) they described the micromachining has a cutting too diameter and feed less than 1 mm. Aramcharoen et al.; (2008) and Zhan et al., (2014) concluded that the micromachining process means the tool diameter falls in a range of 1 to 999 μm and undeformed chip thickness is comparable to tool edge radius or material grain size. According to the above, the micromachining process is a transition technique between the meso and nano machining process as seen in Fig. 1. The micro-milling process is one of the common micromachining processes. It is similar to the conventional milling process in concepts of the cutting process, but it varies in size of the cutting tool. Mini cutting tool and mini tool machining is an inherent feature of the micro-milling process that comes from the miniaturization of components (Zhang et al., 2016).

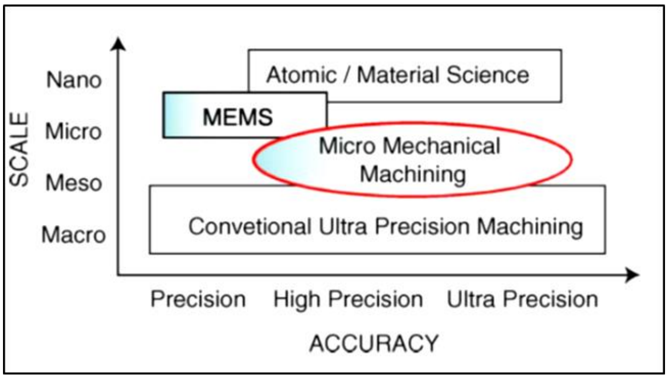

Figure 1. The size of dimension in micromachining procsses (Chae et al., 2006)

2. Micro Machine Tool and High-Speed Spindles

The size and quality of micro-products depend on the properties of the machine tools, which used to produce miniaturized parts, including their overall accuracy and their dynamic performance. Micromachine tools have some advantages such as high rigidity, damping and the ability to operate perfectly based on precision sensors and actuators. Besides, micro-machine tools do not require for use in high production or to achieve the required accuracy only. On the other hand, miniaturization in terms of reducing in size, power, materials, and cost other usefulness be considered. Fig. 2 shows some micro machine tools (Bang et al., 2005;Okazaki et al., 2004;Kussul et al., 1996;Kussul et al., 2002).

Spindle considers an important part of micro machine tools. The rotational speed of spindle must be very high (air bearing spindles exceed 200,000 RPM) to maintain of product's efficiency and surface finishing because the chip removal rate is decreased with small tool diameter (Chae et al., 2006; Kim et al., 2014). Spindle considers an effective tool in the miniaturized cutting tool machine, it plays a significant role in terms of product size, surface quality and accuracy of machined parts. In addition, the quality of machined products will be affected directly by spindle motion error. The hydrostatic and aerostatic spindles are commonly used in micro cutting tools. They have the ability of high revolution speed and high precision of motion. The oil hydrostatic spindle has a high stiffness than aerostatic, but it has low resistance against thermal deformation than the aerostatic spindle. In micro cutting tools, hydrostatic spindles are frequently used to apply the heavy load, but with medium loads, the aerostatic spindles are more suitable to use. A sufficient angular speed, torque, and power can be provided by the spindle drive. The spindle composes in feed drives in machine tools. It held in the spindle housing with bearings (Luo et al., 2005). The integrated single unit of spindle, shaft, and motor provide the stiffness and reducing the motion errors. The accurate and reliable spindle is required to achieve a high quality of products and accuracy of surface roughness (Venkatesh and Izman., 2007; Venkatesh et al., 2016). Jokiel et al., (2004) explored the development of new ultra-high-speed of micro-milling spindles. A novel air-bearing spindle design had been discussed in this study. It runs at very high speeds (450,000 rpm) and provides minimal run-out. Delhaes et al., (2009) mechanism of the new viscous drive has been applied and reached a high speed of 24,000 rpm. Zhou et al., (2015) a novel mechanism has been applied to improve the radial tool run-out of spindles. It has been performed the spindle speed of 125,000 rpm while a tool run-out recorded a 7.5 µm (Gill et al., 2004). They designed a spindle that has a maximum speed of 500,000 rpm and a radial tool run-out of 25 µm, it was an unique for micromachining.

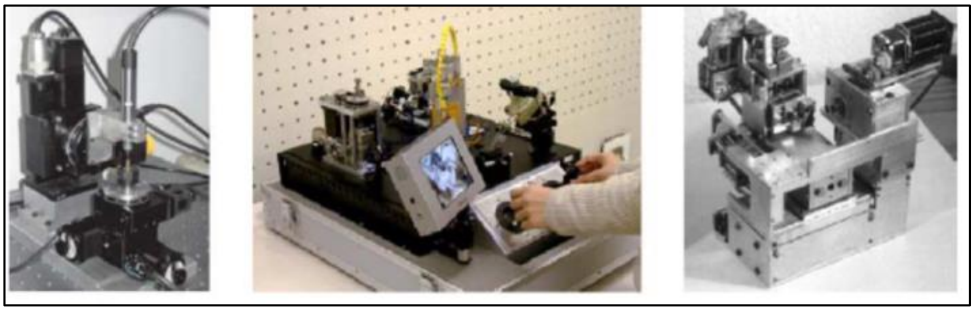

Figure 2. Some examples of micro machine tools (Chae et al., 2006)

3. Micro Cutting Tools

In the micro-cutting process, cutting tools must have special properties to be able to achieve the cutting process under the mini cutting parameters and high speed. Cutting tool materials are classified by a different set of tool materials, because in cutting processes be needing a high resistance in special conditions such as high temperature, high stresses and high friction on workpiece surface by quick removal chip. As a result, Cutting tool materials must have a specific characteristic depending on the type of machining processes, machined workpiece material, and overall thermomechanical process conditions (Grzesik, 2008; Li et al., 2015). The most important features in cutting tool materials must be to have:

- Sufficient hardness at high temperatures to withstand abrasive wear.
- Sufficient resistance against the plastic deformation that happens under high stresses and high temperatures during chip formation. So to prevent the geometry of the cutting edge from plastic deformation
- High fracture toughness to prevent breakage and to resist edge micro chipping especially in interrupted cutting.
- High thermal conductivity to overcome from generated temperatures about the cutting edge.
- High stiffness that required to provide high accuracy.
- Sufficient lubricity to increase welding resistance and to prevent built-up edge formation.

In general, cutting materials must be had high resistance to wear (hard) and sufficient toughness to provide a long tool life for cutting tools. These two characteristics cannot be met together at the same time because of the hard materials are not tough in general and reciprocally (Fig. 3). This problem can be solved successfully by coating the cutting tool with a certain layer of especial and hard material. In micro-cutting machining, the commonly applied materials in addition to using a high-speed steels, CBN(carbon boron nitride), natural diamond-CD and synthetic diamond wheels-SD that have an excellent functional properties and long life (Golabzac and Koziarski, 2005). The following hard cutting materials can be categorized according to DIN ISO 513; tungsten carbide, cutting ceramics, diamond, boron nitride (Adams et al., 2004; Fang et al., 2003; Thepsonthi and Özel; 2013).

The common available micro-end mills that used in micro-milling can be as small as 50 mm in diameter, with a helix angle fabricated by grinding. Fig. 4. depicts a typical two-fluted micro-end mill. The helix angle in the micro-milling tool must be very small to improve its rigidity (Schaller et al., 1999; Onikura et al., 2000).

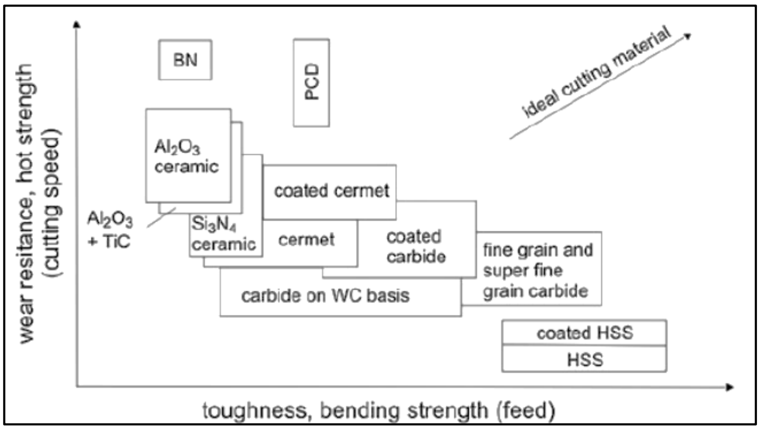

Figure 3. Cutting materials and their wear resistance and toughness (Thepsonthi and Özel, 2013)

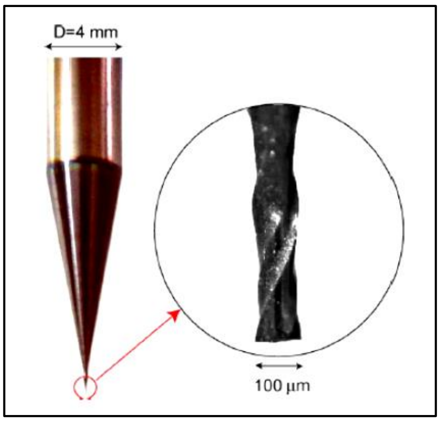

Figure 4. Tungsten carbide micro end mill with two flutes (Schaller et al., 1999).

In micro milling, tool wear and tool life, consider an important matter. Especially, when are used the hard and difficult materials in the cutting process. Elastic deformation of the tool, the round of edge cutting tool, abrasive wear, and breakage are the most encountered problems during micromachining. One of the significant ways to decrease or to overcome these problems is the coating cutting tool. The Coating materials can be contributed to improving the quality of the cutting process (Bouzakis et al., 2012). Many papers have studied the effect of coating materials on improving the micromachining. Ucun et al., (2013) used the coated micro end mills to cut the Inconel 718 superalloy during the micro-milling process. They concluded that coating materials of AlTiN, TiAlN + AlCrN and AlCrN have good results during the cutting process compared to coating materials of TiAlN + WC/C and diamond. Biermann et al., (2013) used AlCrN and TiAlN coated micro end mills to machine the austenitic stainless steel. As a result of the comparison, good surface quality and low tool wear have been obtained with AlTiN coated end mills. Aslantas et al., (2016) investigated the micro-milling process of Ti6Al4V alloy, they used the uncoated and nano-crystalline diamond (NCD) coated tools and TiN and AlCrN coated micro end mills during the cutting process. Poor surface quality and more burr formation were recorded by using uncoated and nano-crystalline diamond (NCD) coated tools.

4. Size Effect and Concept of Removed Chip

In micromachining including the micro-milling process, the size effect phenomenon means the comparability between the edge tool radius with undeformed chip thickness or to applied feed. The tool edge radius in micro-milling significantly affects the micro-cutting process, the opposite of macro machining which the cutting tool edge radius considers as a sharp. Fig. 5. shows the difference between micro and macro cutting process in terms of cutting tool edge radius and uncut chip thickness. In micro-cutting process is usually the uncut chip thickness less than the tool edge radius and the chip forms in the zone of the cutting tool edge radius. Fig. 5.b) shows clearly the existence of the negative rake angle and the relative bluntness of the tool, which plays an important role in increasing the specific cutting forces (Saedon et al., 2016; Vogler et al., 2002; Shaw, 1995).

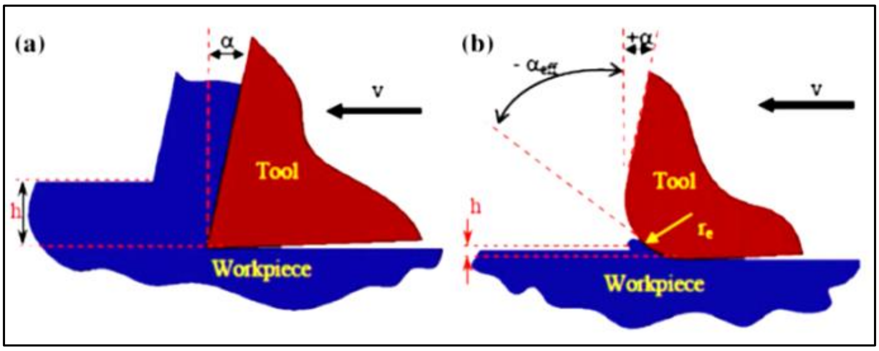

Figure 5. Effect of cutting edge radius to chip thickness a) in macro cutting b) in micro-cutting (Saedon et al., 2016)

The minimum chip thickness h_{min} is specified as the critical value that to be comparable to minimum uncut chip thickness, which removed from a work surface at a cutting edge. In macro machining, in general, the depth of cut is greater than the cutting tool edge radius, and the removed chip from the work surface generates by cutting tool. While in micromachining, the cutting happens at a round of tool edge. The small depth of cut compared to the tool edge radius that causes a large negative rake edge. In this case, the cutting process may be dominated by rubbing and compression instead of removing the chip. This phenomenon is called a ploughing. Ploughing phenomenon causes an elastic recovery of the workpiece, bad surface quality, high cutting forces and increases the possibilities tool damages to happen in the cutting region. The mechanism of chip formation in the micro-cutting process is shown in figure6. Three different cases happen during the cutting process. Figure 6a. shows the first case when the uncut chip thickness is less than a critical minimum chip thickness h_{min}, so the chip cannot be formed and the tool cannot remove any material. The second case that shown in figure 6b. Here, the uncut chip comes near to the minimum chip thickness h_{min}, so, the chip will be started to form by shearing but at this time still, some elastic deformation exists. In the third step, when the uncut chip thickness increases further than the minimum chip thickness h_{min}, here, the elastic deformation becomes lessen and the chip is removed completely as shown in Fig.6.c). Finally, it can be said when the ratio of the depth of cut to tool edge radius less than 1, so the chip cannot be formed and material cannot be deformed (Schmitz et al., 2002; Furukawa and Moronuki, 1988; Lucca et al., 1991; Aramcharoen and Maivenga, 2009; Ucun et al., 2010; Ucun et al., 2013).

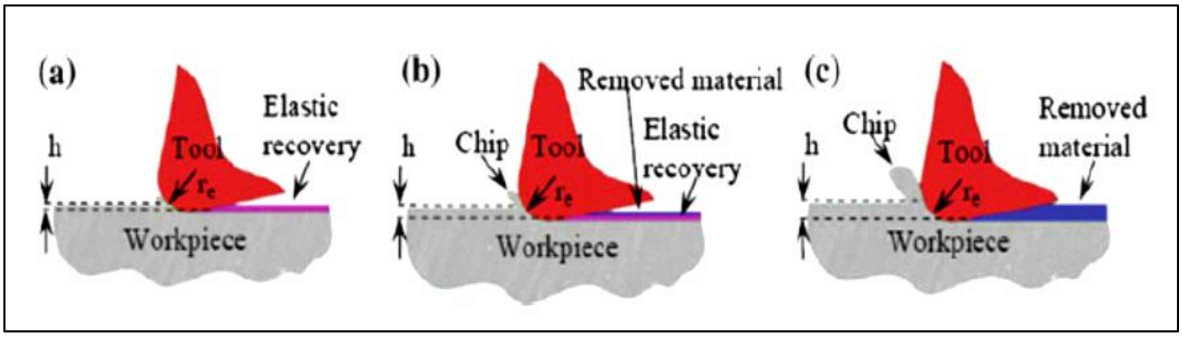

Figure 6. Comparison between chip thickness and chip formation in the micro-cutting process a. $h<h_{min}$, b. $h\approx h_{min}$, c. $h> h_{min}$ (Saedon et al., 2016).

5. Determination of Minimum Chip Thickness

In micromachining processes, including the micro-milling process, the minimum chip thickness is essential in the concept of the cutting process, and the main distinctive factor between macro and micro-cutting process. The minimum chip thickness is relating to the cutting tool radius and this relationship based on the cutting tool edge radius and the workpiece material. During the cutting process, it is very difficult to determine the minimum chip thickness directly, although the possibility to know the tool edge radius (Vogler et al., 2004). The researchers have found the minimum chip thickness by applying finite element (FE) or by experimental works. Vogler et al., (2004) concluded the minimum chip thickness is 0.2 and 0.3 times the edge radius for pearlite and ferrite respectively by using FE simulation for tool steel. Moriwaki et al., (1993) used the FE way to find the minimum chip thickness value with impact the cutting tool radius in the micro-milling process by using the diamond tool to cut a workpiece of copper. The data of FE proved a good agreement with experimental results. Liu et al., (2003) in their work, investigated experimentally chip formation and cutting forces in the micro-milling process. They proved that a sudden change in cutting forces could be indicated to find the minimum chip thickness. This sudden change in cutting forces was considered a transition from plouhing forces to shearing forces as shown in Fig. 7.

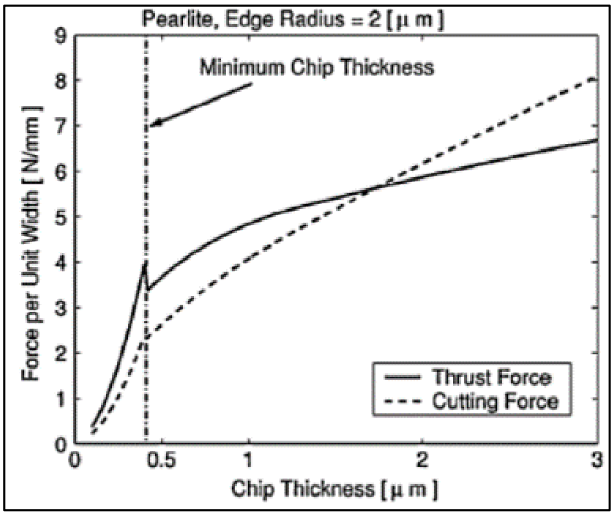

Figure 7. Chip load with cutting forces for pearlite (Liu et al., 2004).

Son et al., (2005) proved the minimum chip thickness has been affected by the friction between the workpiece and cutting tool, i.e. depends on work materials. They also said that a continuous chip is formed at the critical chip thickness, and producing the best surface quality.

6. Cutting Force in Micro Milling

In the micro-milling process, it is very important to control the cutting force due to the breakage of the cutting tool easily. Control of cutting force also results in a better tool life and good surface quality. The most important influencing factors on the cutting force are the cutting tool edge radius because the increasing of edge radius causes difficulty the tool to engage into the workpiece and increases the cutting forces. In addition, the minimum chip thickness, cutting speed, workpiece material, and tool wear are affecting cutting force during the cutting process. In the micro-milling process also, the generated cutting force has a similar character in general with conventional milling, but different in terms of the chip formation mechanism, which causes the shear characteristics to change. Also, because of the cutting force in micro-milling directly relates to chip formation and limits to feed rate. Cutting force also can be determined the tool deflection and bending stress which occurred during the cutting process. In micromachining also, the generated negative rake angle in the cutting edge due to size effect causes instabilities in the cutting force (Chae et al., 2006; Vogler et al., 2004; Bulgurcu, 2017). There are two forces to be considered in terms of the mechanism in the micro-milling process, these are it can be named as ploughing force and shearing force. An available sharp-edged phenomenon in the conventional cutting process cannot be applied in the micromachining process because the chip thickness in micromachining applications can be compared with an edge radius of the tool in size, also due to the large negative rake angle of the cutting tool. The occurred elastic-plastic deformation of the workpiece also changes the cutting force (Kim et al., 2004; Budak, 2000; Dow et al., 2004).

Liu et al., (2004) found through the application of various feed rates during the micro-milling process, cutting force be changed obviously, and the reason belongs to the elastic recovery of the workpiece and the vibration of the tool. As a result, they concluded during the cutting process at low feed rate, cutting be instable and met to ploughing phenomenon. Mamedov and Lazoğlu (2012) in their work, cutting was performed using Al7050, an engineering material in micro-milling, and a 1.5 mm uncoated Tungsten carbide (WC) cutting tool was used. The apparent effect of cutting forces on tool wear and final surface quality has been investigated. A force model is presented in terms of the cutting forces and the mechanics and dynamics of the cutting process. As a result, the accuracy of the presented force model proved to be better under various cutting conditions. Zhang et al., (2016) in their study, cutting forces were investigated in the micro-milling process by using Al6061 as a workpieces and a carbide cutting tool with two flutes. To estimate the general three-dimensional cutting force components, the size effect, tool run-out, and tool deflection were taken in accounted and presented in the proposed analytical estimation model. The parameters of tool run-out and tool deflection were taken from the experimental part. The results of the predictive model has been appropriated the results of experimental work very good.

Campos et al., (2017) in their study, a model of a mechanical cutting force, which adapted 6351-T6 aluminum alloy in micro-milling process was applied, without regard to homogeneous grain characteristics and tool run-out. Cutting forces experimentally were analyzed, taking into account the different feed rates and cutting speeds. This model uses a calibration method depending on the experimental data obtained for calculating the specific cutting force. The model is valid for the cutting process and cutting parameters that performed. As a result, the effect of the feed per tooth and cutting speed on the cutting forces is higher. The mechanical model confirmed this result.

The mode of specific cutting force can be used for future experiments and considered a good estimated mode with error below 15%. Kuram (2017) in his study, the effect of tool attachment length and burr formation on cutting force through the micro milling process of Inconel 718 superalloy was investigated. The different experiments were carried out with a constant number of revolutions, feed, and depth of cut. The tool attachment length of the cutting tool was selected as 10, 15 and 20 mm. Average forces in the x and y directions were recorded. As a result, it has been found that Fx force is greater than Fy force at all cutting tool attachment heights. Both Fx and Fy force increased with increasing cutting tool height as shown in Fig. 8.

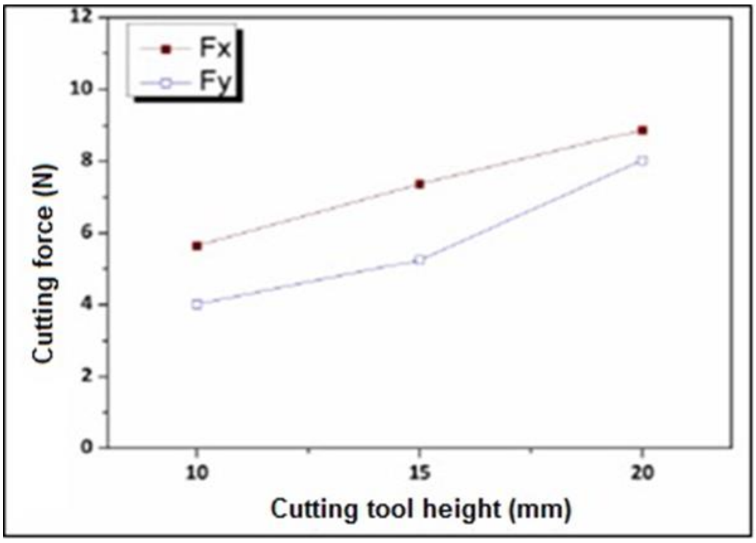

Figure 8. Effect cutting tool attachment height on cutting force (Kuram, 2017).

7. Surface Quality and Burr Formation

At the end of the micro-milling process, surface roughness and accuracy are the most important parameters which provide the quality of the product. In conventional manufacturing processes, additional processing after manufacturing can increase the surface quality of the produced part. Nevertheless, in micro-milling, this is somewhat different and more complex than the macro milling (Wu, 2012; Wang et al., 2016; Wu et al., 2017). Because of the miniature products, having a very small geometric structure and may not be suitable for an additional surface finishing operations. Therefore, in micro-milling, it is important to define the surface formation and the effective parameters on this formation. In the micro-milling process, the most important factor affecting surface quality is the minimum chip thickness. The effect of minimum chip thickness on surface characterization draws attention to many researches (Yuan et al., 1996; Bissacco et al., 2006; Shreyes and Melkote, 2006; Li et al., 2008). The roughness value increases with large values of the depth of cut and feed per tooth (Liu et al., 2003; Weule et al., 2001). On the contract, the low number of revolutions of the cutting tool causes the poor in surface quality due to ploughing phenomenon. Besides, the surface roughness significantly changes with tool geometry. Tool wear causes to change in tool geometry and will, in turn, lead to an increase in roughness values (Lee and Cheung, 2001; Schmitz et al., 2007; Makki et al., 2009). The generated burr formation after machining considers in terms of cleaning and additional processes with high costs undesirable cases. In the conventional milling process, the burrs formed after the manufacturing and it can be cleaned by the additional process. Although the formed burrs in the micro-milling are smaller in size than that deformed in the conventional milling process, the deburring process is more difficult than the conventional milling process (Venkatesh and Izman, 2007; Lee and Dornfeld, 2005; Filiz et al., 2007). During the micro-cutting process, it is very necessary to be taken into account the issue of burr formation and to reduce it to a minimum level (Wan et al., 2013; Afazov et al., 2013). For this, in particular, it is necessary to try to prevent the factors that affect tool wear and residual stresses (Venkatesh et al.,2016).

Many studies about the effect of the cutting parameters on burr formation and surface qualities have been done. Cutting speed, depth of cut, and feed rate as a cutting parameter in terms of the effect on burr formation was investigated for variable Works. Kim et al., (2014) studied in this work the effect of cutting parameters on the burr formation during the micro-cutting process for titanium alloy. The large amount and irregular burrs have been noted with a low feed rate (about 1μm/tooth), on the other, hand they founded that is no significant effect of cutting speed on burr formation. Thepsonthi and Özel (2012) in their study, many experiments were applied during the micro-cutting process of Ti-6Al-4V alloy to study the behavior of burr formation and surface quality with using different cutting parameters. They founded the substantial effect of burr formation is the depth of cut, and the substantial effect of surface quality is the feed rate.

8. Tool Wear

Tool life is a very important issue since cutting tools used in manufacturing processes and it directly affects product quality and cost. The long life of the cutting tools depends on their good abrasion resistance while maintaining their hardness and chemical stability at high temperatures. The size effect in micromachining, especially, the small depth of cut causes the increasing of friction between the cutting tool and machined parts that leads to high temperature and wear. In micro-cutting processes, flank wear and the rounding of tool edge are the most visible. Also, the abrasive wear, adhesive wear, and breakage of cutting tools are the most types of damage. The phenomenon of cutting tool edge and the wear measuring in the micro-scale cutting process are still challenging due to the miniaturization of the cutting tools. Consequently, the quality of the products affected by the increase of tool edge radius (Karubea and Soutomeb, 2003; Perçin et al., 2015; Wu,2012).

The most important effect of the tool wear in the micro-cutting process is the alteration in cutting tool diameter and edge radius which is formed due to the environmental and axial wear that occurs on the cutting tool. As a result, it leads to changes in cutting tool geometry. The environmental wear around the tool creates an increase in edge radius and a decrease in tool diameter. In the micro-milling process, the swift wear of the edge radius of the cutting tool is a critical process, because it directly affects the surface roughness, cutting forces and burr formation. In particular, burr formation in micro-milling increases with tool wear (Özel et al., 2017; Aslantaş et al., 2016; Hatipoğlu and Budak, 2014; Zareena and Velhuis, 2012). Dadgari et al., (2018) studied the relationship between the tool wear of the cutter and the cutting force, the variable cutting speeds have been used during the micro-milling process of Ti-6Al-4V alloy. The flank face of tool subjected to different wear rates against different cutting speeds, and along the cutting tool edge, non-uniform wear has been monitored. Wear average length for each tool flank when cutting length slot of 360mm during apply the different speed has been recorded by Figure 9. In this figure can be noted the average flank wear increased linearly for all cutting velocities, while the Figure 10 represents the SEM image of the flank face of cutting tool milled during altered cutting velocities. It is clearly in this figure, an adhesive wear has been indicated due to coherence of the specimen material, and at the low cutting velocity, the occurred flank wear is low also, although built-up edge forming is directly affected by cutting temperature. As known as the increasing of cutting speed leads to increase the cutting temperature, but it has been noted a small wear rate at high cutting speeds.

In micromachining, it must be understood the interaction between cutting force and tool wear, to ensure a good quality of parts and to provide its requirement, particularly, when hard materials are cut such as stainless steel, titanium alloys, etc. Some researchers like Oliaei et al., (2015) studied the impact of tool wear on cutting forces and surface quality in the micro-milling process. Stavax stainless steel is used as a workpiece. The outputs of this article were recorded with two conditions of the cutting tool (sharp and worm) as shown in Figure 11. Different cutting parameters were applied during the cutting process and optimal parameters were determined. The experimental and theoretical results showed increasing values of cutting force with a worm cutting tool as compared with a sharp cutting tool as shown in Figure 12. Besides, it was noted that surface roughness values were high with a worm cutting tool.

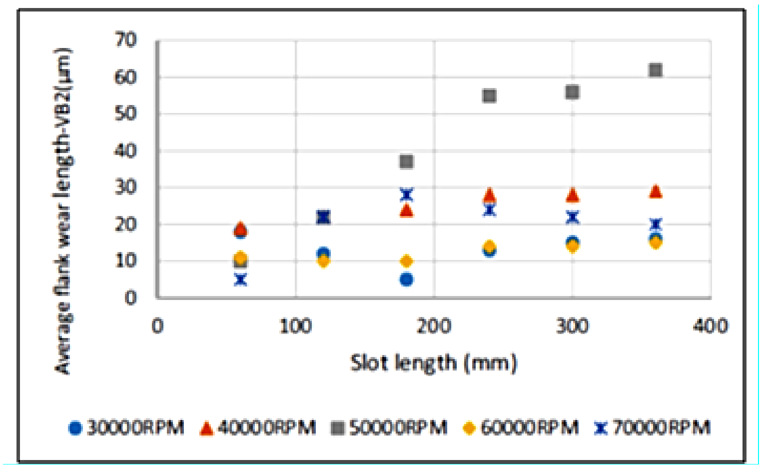

Figure 9. Effect of variable cutting speed on flank wear in cutting tool (Dadgari et al., 2018).

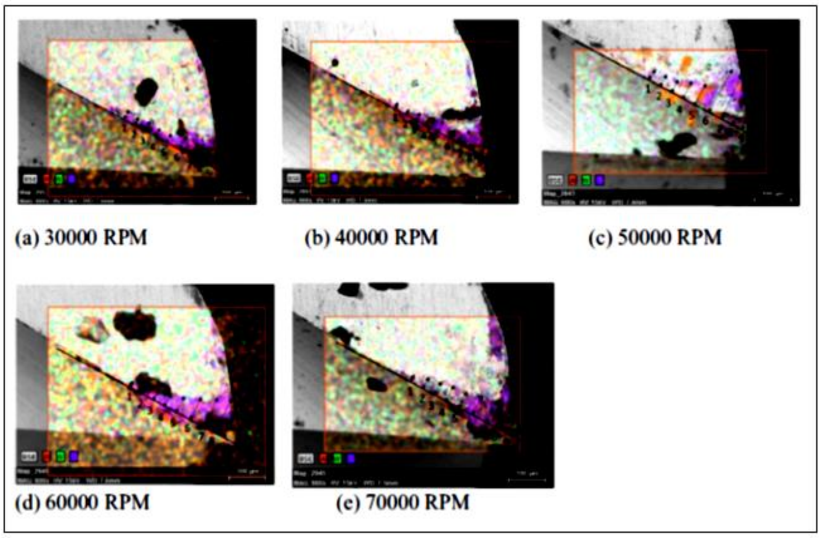

Figure 10. Flaks wear SEM images of the cutting tool after 360mm length machining (Dadgari et al., 2018).

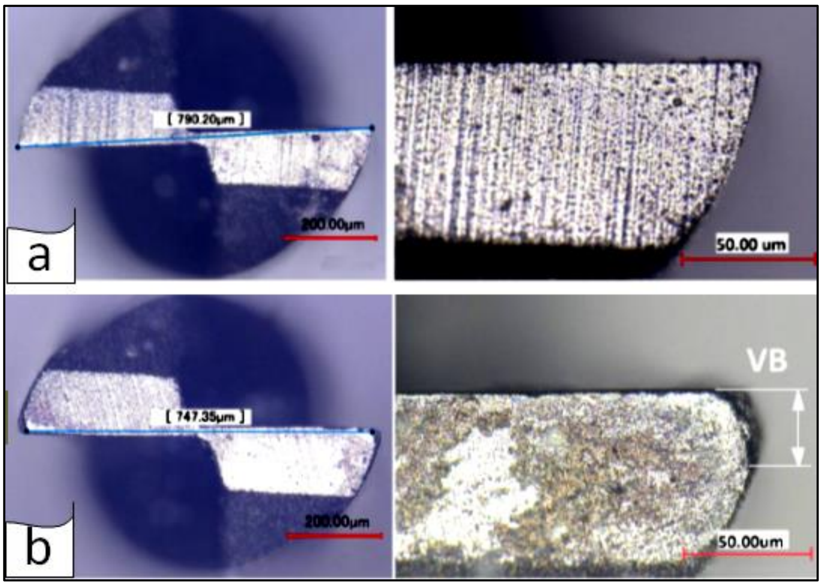

Figure 11: The mages of sharp and worm edges of cutting tool (Oliaei and Karpat, 2015).

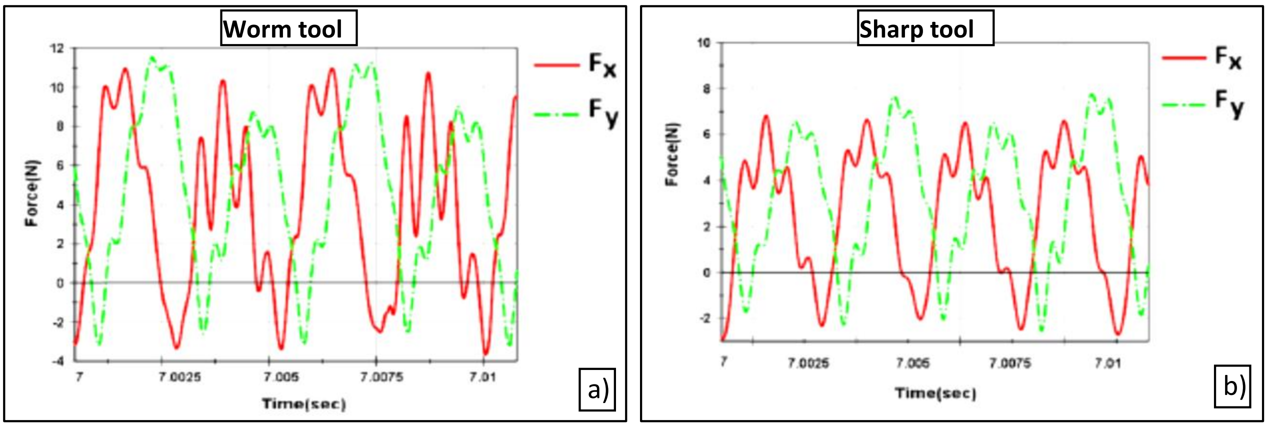

Figure 12: Different Values of cutting forces in the condition of a) the worm and b) sharp cutting tool (Oliaei and Karpat, 2015).

Wu et al., (2015) used the specific cutting force and the analysis of surface roughness to study the relationship between the minimum chip thickness and effective rake angle in the micro-cutting process. They determined the minimum chip thickness at which below it, the specific cutting force increased progressively and the surface quality is very poor.

8. Conclusion

Micromanufacturing systems are seen as the preferred technology for component miniaturization, and it contributes to enhancing economic growth, health, and living standard. The manufacturing of miniaturized components became a big challenge among the workers in this domain. Micromechanical cutting considers as a bridge in terms of size between the macro-micro range. The manufacturing process by the micro-milling process contributed to technology sectors greatly and became a significant competition among the researchers. The micro-end milling processes compared with other processes it has the flexibility and efficiency of using carbide tools and provides the convenience to fabricate mini parts. This work concentrated on some concepts and differences between the macro and micro-cutting processes, although in some cases the removal of the material showed similar direction during machining between them, such as tool wear and chip formation. However, to provide good accuracy and high productivity in the micro-milling process, some factors must be taken into account such as cutting tool characteristics, material properties, cutting force predictions, assembly, modeling, and testing. Also, the minimum chip thickness and its effect on the cutting process are the attractive result and its determination value still a complex issue. The micro-milling process is a proper manufacturing method to support the development in different areas of technology. Micro milling process provides an accuracy, low cost, miniaturized parts, processes of 3D models using ferrous alloys. This work resulted that the investigation of micro-cutting processes is required for more efforts to be able to answer and to discuss the encountered complicated challenges. Generally, in the micro-milling process, chip thickness must be greater than a critical chip thickness to improve the surface quality of products and with maintaining the specimen or tool below the limit of plastic deformation. In addition, the cutting tool geometry can be designed as appropriate for the concept of the micro-cutting process, especially in terms of strength and stiffness to ensure the formation of chips and a regular cutting process. Also, according to the studies done in this field, coated mill ends can be helped and raised the surface qualities of the product. Tool wear effect on cutting forces and surface roughness is unfavorable.

Conflict of Interest

No conflict of interest was declared by the authors.

References

Adams, D., P., Vasile, M., J., Benavides, G., A., Cambel, N., l, 2004. Micro milling of metal alloy with focused ion beam-fabricated tools. Journal of International Societies of Precision Engineering and Nanotechnology 25, 107–113.

Afazov, S.M., Zdebski, D., Ratchev, S.M., Segal, J., Liu, S., 2013. Effects of micro-milling conditions on the cutting forces and process stability. Journal of Materials Processing Technology 213, 671– 684, UK

Aramcharoen, A., Mativenga, P. T., Yang, S., Cooke, K. E., and Teer, D. G., 2008. Evaluation and selection of hard coatings for micro-milling of hardened tool steel. International Journal of Machine Tools and Manufacture, 48 (14) 1578–1584.UK

Aramcharoen, A., Mativenga, P., T., 2009. Size effect and tool geometry in micro-milling of tool steel. Precision Engineering 33, 402–407.

Aslantas, K., Hopa, H., E., Percin, M., Ucun, I., Çiçek, A., 2016. Cutting performance of nanocrystalline diamond (NCD) coating in micro-milling of Ti6Al4V alloy. Precision Engineering, http://dx.doi.org/10.1016/j.precisioneng. 2016.01.009

Aslantas, K., Hopa, H.E., Perçin, M., Ucun, I., Çiçek, A. 2016. Cutting performance of nanocrystalline diamond (NCD) coating in micro-milling of Ti6Al4V alloy. Precis. Eng., 45, (55–66).

Biermann, D., Steiner, M., Krebs, E. 2013. Investigation of Different Hard Coatings for Micro milling of Austenitic Stainless Steel. Procedia Cirp., 7, 246–251.

Bissacco, G., Hansen, H.N., and De Chiffre, L., 2006. Size Effects on Surface Generation in Micro Milling of Hardened Tool Steel. Annals of the CIRP, 55(1), 593-596.

Bouzakis, K.D., Michailidis, N., Skordaris, G., Bouzakis, E., Biermann, D., M'Saoubi, R. 2012. Cutting with coated tools: Coating technologies, characterization methods, and performance optimization. CIRP Ann., 61, 703–723

Budak, E., 2000. Improving productivity and part quality in milling of titanium-based impellers by chatter suppression and force control. Annals of CIRP 49, 31–36.

Bulgurcu, G., 2017. Seleciıon of Micromilling conditions for improved productivity and part quality. Graduate School of Engineering and Natural Sciences Sabancı University, M.Sc Thesis, 95p, Türkiy.

Campos, F.O., Mougo, A. L., Araujo, A. C., 2017. Study of the cutting forces on micro-milling of an aluminum alloy. J Braz. Soc. Mech. Sci. Eng. 39:1289–1296.

Chae, J., Park, S.S., Freiheit, T., 2006. Investigation of Micro-Cutting Operations. International Journal of Machine Tools and Manufacture,46, 313-332.

Dadgari, A., Huo, D., Swailes, D., 2018. Investigation on tool wear and tool life prediction in micro-milling of Ti-6Al-4V. Nanotechnology, and Precision Engineering, 218–225.

Delhaes, G.M.J., Beek, A., vanOstayen, R.A.J., Munnig Schmidt, R.H., 2009. The viscous driven aerostatic supported high-speed spindle. Tribol. Int. 42(11/12), pp 1550–1557, Netherlves

Dornfeld, D., Min, S., Takeuchi, Y., 2006, Recent Advances in Mechanical Micromachining. CIRP Annals–Manufacturing Technology, 55,745-768.

Dow, T., A., Miller, E., L., Garrard, K., 2004. Tool force and deflection compensation for small milling tools. Precision Engineering 28, 31–45.

E. Kussul, T. Baidyk, L. Ruiz-Huerta, A. Caballero-Ruiz, G. Velasco, L. Kasatkina, 1996. Micromechanical engineering: a basis of the low-cost manufacturing of mechanical microdevices using micro equipment. Journal of Micromechanics and Microengineering, 6 (10–425).

E. Kussul, T. Baidyk, L. Ruiz-Huerta, A. Caballero-Ruiz, G. Velasco, L. Kasatkina, 2002. Development of micro machine tool prototypes for micro-factories. Journal of Micromechanics and Microengineering 12, 795–812.

Fang, F., Z., Liu, H., Wu., Liu, X,.D., Y.C., Ng, S.T., 2003. Tool geometry study in micromachining. Journal of Micromechanics and Micro engineering 13 726–731.

Filiz, S., Conley, C.M., Wasserman, M.B., Özdoganlar, O.B., 2007. An Experimental Investigation of Micro Machinability of Copper 101 Using Tungsten Carbide Micro Endmill. International Journal of Machine Tools and Manufacture, 47, 1088-1100,USA

Furukawa, Y., Moronuki, N., 1988. Effect of material properties on ultra-precise cutting process. Annals of CIRP, 37 (1), 113–116

Gill, DD., Jr,. BJ., Ziegert, JC., Payne, SWT., Pathak, JP., 2004. Next-generation spindles for micro-milling. Report by Sandia NationalLaboratories

Gołabczak, A., Koziarski, T.,2005. Assessment method of cutting ability of CBN grinding wheels. International Journal of Machine Tools & Manufacture 45, 1256–1260

Grzesik, W., 2008. Advanced Machining Processes of Metallic Materials Theory, Modelling, and Applications. pp 478, Elsevier Science, Netherlands.

Hatipoğlu E. ve Budak E., 2014. Mikro Frezeleme İşleminde Kesme Parametrelerinin Yüzey ve Talaş Oluşumuna Etkisinin Deneysel Olarak İncelenmesi. 5.Ulusal Talaşlı İmalat Sempozyumu, Türkiye

Jokiel, Jr., B., Gill, D., D., Ziegert, J., C., Payne, S., W., T., Pathak, J., P., 2004. SAND 6445, Unlimited Release, Report

Karubea, S., Soutomeb, T., 2003. The effect of tool nose radius in ultrasonic vibration cutting of hard metal. International Journal of Machine Tools and Manufacture, V.43, Issue 13, (1375-1382).

Kim, B., Schmittdiel, M., C., Degertekin, F., L., Kurfess, T., R., 2004. Scanning grating micro interferometer for MEMS metrology. Journal of Manufacturing Science and Engineering 126, 807–812

Kim, D., H., Lee, P., Lee, S., W., 2014. Experimental Study on Machinability of Ti-6Al-4V in Micro End-Milling. Proceedings of the World Congress on Engineering 2014 Vol II, ISBN: 978-988-19253-5-0.

Kuram, E., 2017. Kesici Takım Bağlama Uzunluğunun Mikro Frezelemede Takım Aşınması, Kuvvetler ve Çapak Boyutu Üzerindeki Etkileri. Fen ve Mühendislik Dergisi, Cilt 19, Sayı 55, Türkiye

Lee, K., Dornfeld, D.A., 2005. Micro-Burr Formation and Minimization Through Process Control. Precision Engineering, 29, 246-252.

Lee, W.B., Cheung, C.F., 2001. A Dynamic Surface Topography Model for The Precision of Nano-Surface Generation in Ultra-Precision Machining. International Journal of Mechanical Sciences, 43, 961-991.

Li, H., Lai, X., Li, C., Feng, J., Ni, J., 2008. Modeling and Experimental Analysis of the Effects of Tool Wear, Minimum Chip Thickness and Micro Tool Geometry on the Surface Roughness in Micro-End-Milling. Journal of Micromechanical and Microengineering, 18(2), 1-12.

Li, W., Zhou, Z.X., Xiao, H., Zhang, B., 2015. Design and evaluation of a high-speed and precision micro spindle. Int. J. Adv. Manuf. Technol. Vol.78 (5), pp 997–1004, London

Liu, K., Li, X., P., Rahman, M., 2003. Characteristics of high-speed micro-cutting of tungsten carbide. Journal of Materials Processing Technology 140, 352–357.

Liu, X., DeVor, R. E., Kapoor, S. G., and Ehmann, K. F., 2004. The mechanics of machining at the microscale: assessment of the current state of the science. Journal of Manufacturing Science and Engineering, Transactions of the ASME, 126 (4) 666–678.

Liu, X., Jun, M,.B., Devor, R., E., Kappor, S., G., 2004. Cutting Mechanisms and their Influence on Dynamic Forces, Vibrations and Stability in Micro-end Milling. Proceedings ASME International Mechanical Engineering Congress and Exposition. Anaheim California, 13–20.

Lucca, D., A., Rhorer, R,.L., Komanduri, R., 1991. Energy dissipation in the ultra-precision machining of copper. Annals of CIRP, 40, 559–562.

Luo, X., Cheng, K., Webb, D., 2005. Design of ultraprecision machine tools with applications to manufacture of miniature and micro components. Journal of Materials Processing Technology, Vol. 167, Issues 2-3, pp 515-528, UK.

Makki, H., Heinemann, R., Hinduja, S., Owodunni, O., 2009. Online Determination of Tool Run-Out and Wear Using Machine Vision and Image Processing Techniques. 5th Virtual Conference Innovative Production Machines and Systems, 6-17 July, (CD-ROM).

Mamedov A. ve Lazoğlu İ., 2012. Mikro Frezeleme için Mekanistik kuvvet Modeli. 3. Ulusal Tasarım İmalat ve Analiz Kongresi, 175-183, Türkiye.

Masuzawa, T., 2000. State of the Art of Micromachining. Annals of CIRP, 49(2): 473–488.

Masuzawa, T., and Tönshoff, H. K., 1997. Three-dimensional micromachining by machine tools. CIRP Annals - Manufacturing Technology, 46 (2) 621–628. Germany.

Moriwaki, T., Sugimura, N., Luan, S., 1993. Combined stress material flow and heat analysis of orthogonal micromachining of copper. Annals of CIRP 42,,75–78.

Oliaei, S., N., B., Karpat Y., 2015. Influence of tool wear on machining forces and tool deflections during micro-milling. Springer-Verlag, London. DOI 10.1007/s00170-015-7744-4

Onikura, H., Ohnishi, O., Take, Y., 2000. Fabrication of micro carbide tools by ultrasonic vibration grinding. Annals of CIRP 49.

Özel, T., Olleak, A., Thepsonthi, T., 2017. Micro milling of titanium alloy Ti-6Al-4V: 3-D finite element modeling for prediction of chip flow and burr formation. Prod. Eng. Res. Devel, 11: 435–444.

Perçin, M., Aslantaş, K., Ucun, İ., Çiçek, A., 2015. Mikro Frezeleme İşleminde Kesme Koşullarının Takım Aşınması ve Yüzey Pürüzlülüğü Üzerindeki Etkisi. 8. Müh. ve Teknoloji Sempozyumu, 14-15 Mayıs/Çankaya Üniversitesi/Ankara, s 45-50

Saedon, J., Norrdin N., A., Yahaya, M., A., Kasim, M., S., and Mohamad Nor, NH., 2016. Investigation of Cutting Edge Radius Effect in Macro-machining and Micro-machining. Regional Conference on Science, Technology and Social Sciences (RCSTSS 2014), DOI 10.1007/978-981-10-0534-3_2, 17-26p.

Schaller, T., Bohn, L., Mayer, J., Schubert, K., 1999. Microstructure grooves with a width of less than 50 mm cut with ground hard metal micro end mills. Precision Engineering 23 229–235.

Schmitz, T., Couey, J., Marsh, E., Mauntler, N., Hughes, D., 2007. Runout Effects in Milling: Surface finish, Surface Location Error, and Stability. International Journal of Machine Tools and Manufacture, 47, 841–851

Schmitz, T., L., Davies, M., Kennedy, M., D.,2002. Tool point frequency response prediction for high-speed machining by RCSA. Journal of Manufacturing Science and Engineering, 123, 700–707.

Shaw, M.C., 1995. Precision finishing. Annals of CIRP 44 (1) 343– 348.

Shreyes, K.L., Melkote, N., 2006. Effect of Plastic Side flow on Surface Roughness in the Micro-Turning Process. International Journal of Machine Tools and Manufacture, 46, 1778–1785.

Son, S., M., Lim, H,.S., Ahn, J., H., 2005. Effects of the friction coefficient on the minimum cutting thickness in micro-cutting. International Journal of Machine Tools and Manufacture 45, 529–535.

Thepsonthi, T., Özel, T., 2012. Multi-objective process optimization for micro-end milling of Ti6Al4V titanium alloy. Int J. Adv Manuf Technol, 63:903–914

Thepsonthi, T., Özel, T., 2013. Experimental and finite element simulation-based investigations on micro-milling Ti-6Al-4V titanium alloy: Effect of CBN coating on tool wear. Journal of Materials Processing Technology, 213, 532-542

Ucun, I., Aslantas, K., Bedir, F. 2013. An experimental investigation of the effect of coating material on tool wear in micro-milling of Inconel 718 superalloy. Wear, 300, 8–19

Ucun, İ., Aslantaş, K., Bedir, F. 2010. İnconel 718 Süper Alaşımının İşlenmesinde Kaplanmış Mikro Takımların Aşınma Davranışları ve Performans Analizi. Makine Teknolojileri Elektronik Dergisi, Cilt: 7, No: 4, 47-55.

Venkatesh, V. C., Izman, S., 2007. Precision Engineering. pp 436, Tata McGraw-Hill, USA.

Venkatesh, V., Swain, N., Sırınıvas, G., Kumar, P. andBarshilia, H.C., 2016. Review on the machining characteristics and research prospects of conventional micro-scale machining operations. Materials and Manufacturing Process, 32(3), 235-262.

Vogler, M., P., Devor, R., E., Kapoor S., G., 2004. On the modeling and analysis of machining performance in micro end milling. Journal of Manufacturing Science and Engineering 126 (4) ,685–705.

Vogler, M.P., Liu, X., Kapoor, S., G., Devor, R., E., Ehmann, K., F., 2002. Development of mesoscale machine tool (mMT) systems. Society of Manufacturing Engineers MS n MS02-181 1–9.

Wan, Y., Change, K., Sun, S., 2013, An innovative method for surface defects prevention in micro milling and its implementation. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Proc IMechE Part J: Engineering Tribology 227(12) 1347–1355.

Wang, Z., Kovvuria, V., Araujob, A., Baccic M., Hunga, W.N.P., Bukkapatnama, S.T.S., 2016. Built-up-edge effects on surface deterioration in micro-milling Processes. Journal of Manufacturing Processes 24, 321–327. Brazil.

Weule, H., Huntrup, V., Tritschle, H., 2001. Micro-Cutting of Steel to Meet New Requirements in Miniaturization. Annals of the CIRP, 50(1), 61-64.

Wu X, Li L, Zhao M, He N, 2015. Experimental investigation of specific cutting energy and surface quality based on negative effective rake angle in micro turning. Int J Adv Manuf Technol 82:1941–194

Wu, X., Li, L., He, N., 2017. Investigation on the burr formation mechanism in micro-cutting. Precision Engineering, 47, pp191–196.

Wu, T., 2012. Tooling Performance in Micro Milling: Modelling, Simulation, and Experimental Study. School of Engineering and Design, Brunel University, Doctorate Thesis, 229pp, England.

Y. Okazaki, N. Mishima, K. Ashida, 2004. Micro factory-concept, history, and developments. Journal of Manufacturing Science and Engineering 126, 837–844.

Y.B. Bang, K. Lee, S. Oh,2005. 5-Axis micro milling machine for machining micro parts. Int J Advanced Manufacturing Technology, 25: 888–894

Yuan, Z.J., Zhou, M., Dong, S., 1996. Effect of Diamond Tool Sharpness on Minimum Cutting Thickness and Cutting Surface Integrity in Ultra-Precision Machining. Journal of Materials Processing Technology, 62(4), 327–330.

Zareena, A., R., Veldhuis, S., C., 2012. Tool wear mechanisms and tool life enhancement in ultra-precision machining of titanium. Journal of Materials Processing Technology, 212, 560-570

Zhan, z., Liang Li, Ning H. & Rabin Sh., 2014. An experimental study on grinding parameters for manufacturing PCD micro-milling tool. International Journal of Advanced Manufacturing Technology, V. 73, Issue 9, pp 1799–1806. London.

Zhang, X. , Ehmann, K., F., T., Wang, W., 2016. Cutting forces in micro-end-milling processes. International Journal of Machine Tools & Manufacture 107, 21–40, China

Zhou, Li, W., Xiao, Z.X., Zhang, H., B., 2015. Design and evaluation of a high-speed and precision micro spindle. Int. J. Adv. Manuf. Technol. Vol.78 (5), pp 997–1004, London.