11th Brazilian Congress on Manufacturing Engineering
May 24th-26th, 2020, Curitiba, PR, Brazil

A CONTRIBUTION ON THE USE OF REPLICAS FOR MICROMILLING EXPERIMENTAL TRIALS

Déborah de Oliveira
University of Brasilia, Departament of Mechanical Engineering, Campus Univeritário Darcy Ribeiro. Asa Norte, Brasília – DF, Brazil, Zip code: 70.910-900.
oliveira.deborah@unb.br

Raphael Lima de Paiva
Federal University of Piauí, School of Mechanical Engineering, Campus Universitário Ministro Petrônio Portella – Ininga, Teresina – PI, Brazil, Zip code: 64049-550.
raphaellimap@ufpi.edu.br

Marcio Bacci da Silva
Federal University of Uberlândia, School of Mechanical Engineering, Campus Santa Mônica – Uberlândia – MG, Brazil, Zip code 38408 100.
mbacci@ufu.br

Abstract. *Micromachining has many definitions, but it is defined by many authors as a process in which the tool as 1 to 1000 µm. Due to its small sizes the tool cannot be considered perfectly sharp and therefore many of the theories applied for macro machining cannot be used. In this sense many authors tried to develop computational and experimental studies to contribute to the comprehension of those processes. Those authors usually varied the workpiece material, the cutting tool, cutting parameters and the outputs they measured, however there is still no consensus about the use of replica. In this sense, this work aims to contribute to the discussion of the use of replicas in the micro machining process. Experimental trials of micromilling with one replication each were performed in Inconel 718 with different cutting speeds. The output parameter analyzed was the surface finish (Ra parameter). A statistical analysis of variance (ANOVA) was performed in order to verify the statistic influence of cutting speed and replication trials, as well as their interaction. The results showed that the variation of surface finish between test and replica was statistically significant, although the influence of cutting speed was more expressive.*

Keywords: *Micromilling, Inconel 718, Replicas, Surface finish.*

1. INTRODUCTION

Micromilling does not have a single definition yet, although many authors based the micro cut definition on the unformed chip thickness, like Masuzawa (2000), Ng *et al.* (2006) and Venkatesh *et al.* (2016), one of the most accepted method to consider a machining process micro is if it has cutting tools with dimensions varying from 1 µm to 1000 µm (Camara *et al.* 2012, Jain *et al.*, 2015 and Ziberov *et al.*, 2016). With those small dimensions the cutting edge happens to have the same scale as the material microstructure (Liu *et al.*, 2007) and cannot be considered perfectly sharp, instead having a negative rake angle that can induce the high plowing common in micromachining (Wang *et al.*, 2016). Therefore, size effect, micro tool geometry and workpiece material can interfere in the process results in terms of: roughness of the machined surfaces (Ahmadi *et al.*, 2018), burr formation (Yadav *et al.*, 2017), chip formation (De Oliveira *et al.*, 2019a), cutting forces and cutting vibration (Gomes *et al.*, 2021), and microtool wear (Alhadeff *et al.*, 2019).

According to Camara *et al.* (2012) there are several factors that still need to be understood in micromachining and that in general, researchers choose materials with good machinability to simplify their studies. However, according to Wang *et al.* (2017) studying the micromilling of low-machinability alloys is one of the ways to contribute to the understanding of the process. Considering a difficult to cut material with vast industrial application and specific properties, the Inconel 718 stands out. Focusing on the micromilling of Inconel 718, cold hardening, high wear rates and high plowing, that hinds chip generation are the main difficulties when micromilling (Wang *et al.*, 2017). Added to it, ductile matrix, and the presence of coherent precipitated carbides of high hardness (Reed, 2006) can make it even harder to micromill.

Ucun *et al.* (2013) studied the effect of the coating on tool wear when micromilling Inconel 718. They used a 768 µm diameter tool, with the following coatings: TiAlN + AlCrN, DLC, AlTiN, TiAlN + WC / C and AlCrN. The cutting speed was 48 m / min, the feeds 1.25 µm, 2.50 µm, 3.75 µm and 5.00 µm and the cutting depths 100 µm, 150 µm and 200 µm. The authors observed that flank wear, due to the abrasive wear mechanism, was the most frequent type of wear. The authors also observed a reduction in the wear rate for coated tools compared to uncoated tools and in the same way, among the coatings, the best were: DLC and TiAlN + WC / C. Unlike the macro process, greater wear was observed for smaller feeds and small depths of cut. Regarding the use of lubricant, Ucun *et al.* (2013) used Coolube 2210 vegetable oil, applied via MQL technique with a flow rate of 150 ml / h and found that lubrication significantly increased tool life and prevent chip adhesion. In other study regarding the cutting fluid, De Oliveira *et al*. (2020) studied the cutting fluid application frequency in micromilling Inconel 718, comparing two frequencies: lower flow rate (40.7 ml/h in 30 pulses per minute) and higher flow rate (270.0 ml/h in 200 pulses per minute). The authors verified that the cutting fluid can improve surface integrity by reducing surface roughness values, avoiding adherence of material on the surface, and reducing burr formation for Inconel 718. The higher rate could reduce the surface roughness in 60%. The lower frequency is not suitable for micromilling Inconel 718.

Considering what have been presented, it is possible to notice that there is still the need of studying the Inconel micromilling, and regarding those studies, it is important to use the right methodology whether in the experimental design, the parameters selection or in the outputs analyzed, in this sense, this work aims to contribute to the comprehension of the replica results of micromilling experiments, that are not widely used.

2. MATERIALS AND METHODS

To evaluate the influence of replicas in micro machining, the process select is the micromilling. The tool is a micro end mill ultra-refined cemented carbide, coated with (Al, Ti)N, 400 µm diameter, 2 flutes (MS2MSD0040) from Mitsubishi. The machine is a Mini-mill / GX CNC, that has a maximum spindle speed (n) of 60000 rpm and 3 axes with position resolution of 0.1 µm, manufactured by Minitech Machinery Corporation. The material is the refractory alloy Inconel 718, 535 HV (De Oliveira *et al.*, 2019b).

The trials consisted in machining micro slots of 15 mm in the Inconel surface and perform a replica with a new tool, all the tools used were observed in a scanning electron microscope (SEM) to verify their integrity before the machining. Four different cutting speeds were evaluated: 13.8, 25.1, 50.3 and 75.4 m/min. The other cutting parameters were kept constant as shown in Tab. 1.

Following the methodology proposed by De Oliveira *et al*. (2020), cutting fluid in flow rate of 270.0 (ml/h) was applied in all the trials. The cutting fluid was Coolube 2210EP, manufactured by UNIST. The system was set to deliver the fluid at an air pressure of 33 psi (0.23 MPa), at 200 pulses per minute, the position of nozzle is presented in Fig. 1.

After the machining, a Form Talysurf Intra Taylor Hobson® profilometer was used to measure the surface roughness in the middle of the slots. The profilometer has a measurement range of 1.0 mm and 16 nm resolution. The parameter selected was the arithmetic average roughness (Ra) to be measured with a cut off of 0.8 mm and a gaussian filter. For each slot with different parameter, been trial or replica, three measurements were performed, and the results will be presented as the mean value.

Table 1. Cutting parameters

Parameter:	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Spindle speed n (rpm)	11 000	20 000	40 000	60 000
Cutting speed v_c (m/min)	13.8	25.1	50.3	75.4
Feed rate v_f (mm/min)	110	200	400	600
Feed per tooth f_z (µm/tooth)	5			
Axial depth of cut a_p (µm)	40			
Radial depth of cut a_e (µm)	400			

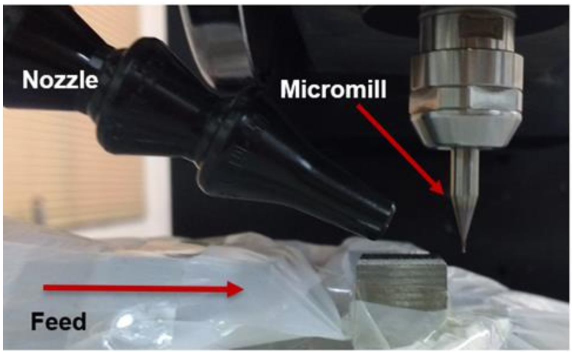

Figure 1. Schematic view of the micromilling process and cutting fluid application (De Oliveira *et al.*, 2020).

Also, considering the high variation in results usually obtained by the literature, and the variation in the replica results, an analysis of variance (ANOVA) was performed by considering the 2-level factor "trial" (test and replica) and the 4-level factor "cutting speed", as well as their interaction. A confidence interval of 95% ($\alpha = 0.05$) was considered.

3. RESULTS AND DISCUSSION

The surface roughness Ra as a function of cutting speed is shown in Fig. 2, for both test and replica trials. Worth mentioning that the mean values of Ra parameter for all experimental trials were in the range of 0.10-0.20 µm, which are about 75% lower in comparison to the Ra values reported by Mian *et al.* (2011). Furthermore, it can be noticed from Fig. 3 that the replica trials resulted in machined surfaces with higher values of Ra, especially for the cutting speeds of 25.1 m/min and 50.3 m/min. In order to verify whether the results between test and replica were statistically significant a statistical analysis was performed. The ANOVA results are shown in Tab. 2, where DF, SS and MS stands for the degree of freedom, sum of square and mean square, respectively. The pareto chart of the standardized effects is shown in Fig. 3.

From Tab. 2, it can be noticed that all the factors, including their interaction, presented a P-value lower than 0.05 and, therefore, were statistically significant for the surface finish results considering the conditions used in this work. Furthermore, one notes from Fig. 3 that the most significant factor for Ra parameter was the cutting speed, followed by the trial (test or replica) and the interaction between these factors. The graphs of main effects and interaction are shown in Fig. 4.

From Fig. 4(a), one notes that the values of surface roughness (Ra parameter) measured after replica trials were, in average, 22% higher in comparison to those measured after the first experimental trials (Test). According to Machado *et al.* (2015), the final condition of a given machined surface is a result of a process which includes plastic deformation, material shearing, elastic recovery, heat generation, vibrations, residual stresses, and even chemical reactions. All these factors influence the finishing of machined surface and, due to the inherent variability of such phenomenon, variations in surface roughness are then expected in different trials, even though machining with the same cutting and cooling-lubrication conditions.

In the case of face milling, the use of multi-toothed cutters and the vibrations due to the interrupted nature of cutting process, among other effects, contribute to a less uniform surface finish in comparison to turning process, for instance (Stephenson and Agapiou, 2016). Additionally, the inherent characteristics of micro machining process, such as the negative effective rake angle that contributes to plowing phenomenon (Wang *et al.*, 2016), as well as the not perfectly sharp cutting edges with similar dimensions as the material microstructure (Liu *et al.*, 2007), further contribute to surface finish variability, especially when milling difficult-to-machine materials such as Inconel 718. Jaffery *et al.* (2016) also point out the difficult to reproduce the same micro-tools dimensions (e.g., edge radius, rake and clearance angle) for tools having identical specifications, which further influences the capability and repeatability of the micro-milling process.

Regarding the effect of cutting speed on surface finish results, one notes from Fig. 4 that roughness Ra of machined surface increased with cutting speed until 50.3 m/min, presenting a sharp decrease (36% in average) for further increase in cutting speed (v_c = 75.4 m/min). The effect of cutting speed on surface finish in micromachining process depends not only on its variation level, but also on other process parameters (e.g., depth of cut) and workpiece/tool materials.

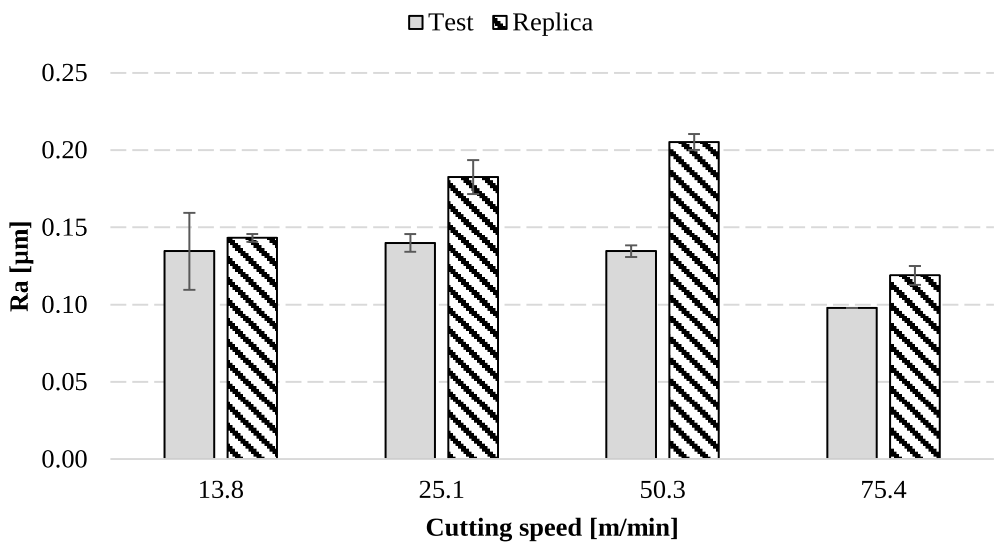

Figure 2. Surface finish (Ra parameter) results.

Table 2. ANOVA results for Ra.

Source	DF	SS	MS	F-Value	P-Value
Main effects					
Trial	1	0.007668	0.007668	71.69	0.000
vc [m/min]	3	0.013558	0.004519	42.25	0.000
2-Way Interactions					
Trial*vc [m/min]	3	0.003327	0.001109	10.37	0.000
Error	16	0.001711	0.000107		
Total	23	0.026265			

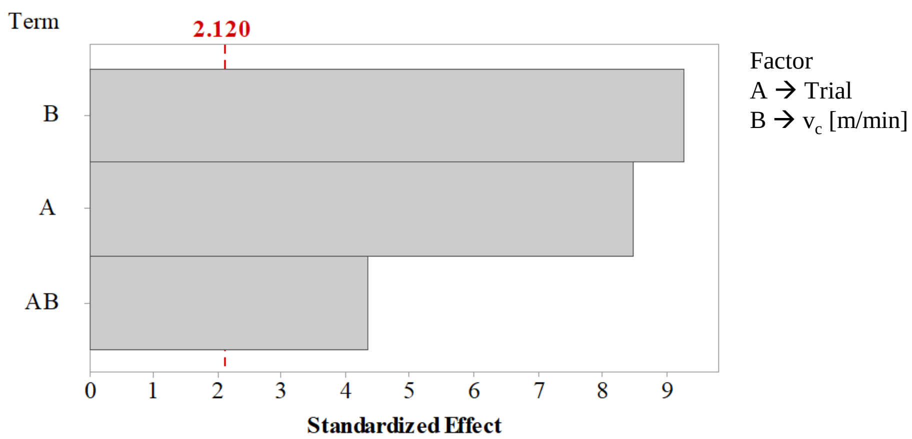

Figure 3. Pareto chart for Ra. Standardized effects, α = 0.05.

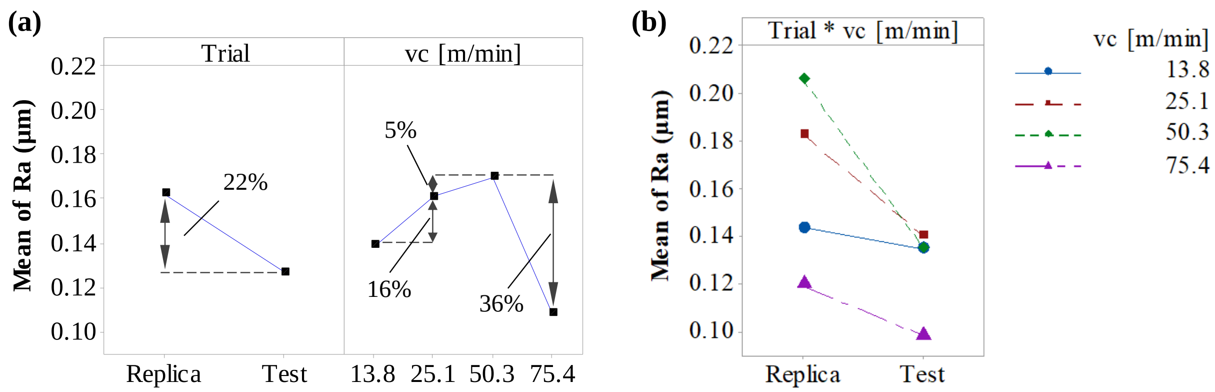

Figure 4. Main effects (a) and interaction (b) graphs for surface finish results.

Dos Santos *et al.* (2015) evaluated the surface finish (Ra parameter) of the UNS 32205 duplex stainless steel after micro-milling with coated carbide tool. The authors observed no significant influence on surface finish by increasing cutting speed from 24 m/min to 36 m/min. Bandapalli *et al.* (2017) analyzed the effect of cutting speed, feed rate and depth of cut on surface finish (Ra parameter) of Ti-6Al-4V after micro-milling process and observed that the most influent cutting parameter on roughness was the feed rate, followed by depth of cut. The authors verified that, although the cutting speed presented the lower influence on surface finish, there was a tendency of surface finish improvement (lower values of Ra) by increasing cutting speed in the levels analyzed (47, 94 and 141 m/min). With respect of micro-milling of Inconel 718 with carbide tools, Mian *et al.* (2011) observed an increase in surface roughness (Ra parameter) with cutting speed in the range of 10-45 m/min, which is in good agreement to results found in this work (Fig. 4).

Worth mentioning that the increase in surface roughness with cutting speed in the range of 13.8-50.3 m/min was only significantly observed in the results of this work due to the use of replica. As it can be noticed from Fig. 4(b) and Fig. 2, the first experimental trials (Test) did not present significant variation in surface finish when machining with these cutting speeds. This result explains the statistical significance of the interaction between the factors trial and cutting speed, and it also shows the importance in considering the use of replica in micromachining experiments.

4. CONCLUSIONS

After the experimental trial and the statistical analysis performed in this work, the following conclusions can be drawn:

- The use of replica in experimental trials presented a statistical significance for surface finish results. In comparison to the first experimental trials (Test), the surface roughness (Ra parameter) of workpiece was, in average, 22% higher on the replica trials for the conditions used in this work.
- The cutting speed presented more statistical influence on surface finish results in comparison to the use of replica. The surface roughness increased with cutting speed in the range of 13.8-50.3 m/min. A strong improvement (36% reduction in Ra) was observed by increasing the cutting speed from 50.3 m/min to 75.4 m/min.
- The use of replica was crucial to verify the effect of cutting speed on surface finish of Inconel 718 after micromachining with lower cutting speeds (up to 50.3 m/min).

5. ACKNOWLEDGEMENTS

The authors are thankful to CAPES, CNPQ, FAPEMIG, and to the Department Mechanical Engineering, Faculty of Technology, of University of Brasilia.

6. REFERENCES

Ahmadi, M., Karpat, Y., Acar, O. and Kalay, Y. E., 2018. "Microstructure effects on process outputs in micro scale milling of heat treated Ti6Al4V titanium alloys". In *Journal of Materials Processing Technology*, Vol. 252, p. 333–347.

Alhadeff, L.L., Marshall, M. B., Curtis, D.T. and Slatter, T., 2019, "Protocol for tool wear measurement in micro-milling". In *Wear*, Vol. 420–421, p. 54–67.

Bandapalli, C., Sutaria, B. M., Bhatt, D. V., Singh, K. K., 2017. "Experimental Investigation and Estimation of Surface Roughness using ANN, GMDH & MRA models in High Speed Micro End Milling of Titanium Alloy (Grade-5)". *Materials Today: Proceedings 4*. 1019-1028.

Camara, M.A., Rubio, J.C.C., Abrão, A. M. and Davim, J. P., 2012. "State of the Art on Micromilling of Materials, a Review". In *Journal of Materials Science & Technology*, Vol. 28, p. 673–685.

De Oliveira, D. Gomes, M. C. and Da Silva, M.B., 2020. "Influence of cutting fluid application frequency on the surface quality of micromilled slots on Inconel 718 alloy". In *48th SME North American Manufacturing Research Conference, NAMRC 48, Ohio, USA, Procedia Manufacturing*, Vol. 48, p. 553–558.

De Oliveira, D., Da Silva, R.B. and Gelamo, R.V., 2019b. "Influence of multilayer graphene platelet concentration dispersed in semisynthetic oil on the grinding performance of Inconel 718 alloy under various machining conditions". In *Wear*, Vol. 426–427, p. 1371–1383.

De Oliveira, D., Gomes, M. C. And Da Silva, M. B., 2019a. "Spheroidal chip in micromilling". In *Wear*, Vol. 426–427, p. 1672–1682.

Dos Santos, A. G., Cunha, D. F., Ziberov, M., Hung, W. N., Jackson, M. J., Da Silva, M. B., 2015. "Avaliação da Qualidade de Microcanais Fabricados por Microfresamento no Aço Inoxidável Duplex UNS 32205". In: Anais do *8º Congresso Brasileiro de Engenharia de Fabricação*.

Gomes, M.C., Brito, L. C., Da Silva, M.B. and Duarte, M.A.V, 2021. "Tool wear monitoring in micromilling using Support Vector Machine with vibration and sound sensors". In *Precision Engineering*, Vol. 67, p. 137–151.

Jaffery, S. H. I., Khan, M., Ali, L., Mativenga, P. T., 2016. "Statistical analysis of process parameters in micromachining of Ti-6Al-4V alloy". *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*. 230(6):1017-1034.

Jain, V.K., 2015. "Special issue on micromanufacturing", In *Int. J. Adv. Manuf. Technol.*, Vol. 85, p. 1937–1939.

Liu, K. and Melkote, S. N., 2007. "Finite element analysis of the influence of tool edge radius on size effect in orthogonal micro-cutting process". In *International Journal of Mechanical Sciences*, Vol. 49, p. 650–660.

Machado, A. R., Abrão, A. M., Coelho, R. T., Da Silva, M. B., 2015. "Teoria da Usinagem dos Materiais", 3º ed., São Paulo, Blucher.

Masuzawa, T., 2000. "State of the art of micromachining". In *CIRP-Annals of Manufacturing Technology*, Vol. 49, p. 473–488.

Mian, A.J., Driver, N. and Mativenga P.T., 2011. "Identification of factors that dominate size effect in micro-machining". In *International Journal of Machine Tools & Manufacture*, Vol. 51, p. 383–394.

Ng, C.K., Melkote, S.N., Rahman, M. and Kumar, A.S., 2006. "Experimental study of micro- and nano-scale cutting of aluminum 7075-T6". In *Int. J. Mach. Tools Manuf.*, Vol. 46, p. 929–936.

Reed, R. C., 2006. "*The Superalloys Fundamentals and Applications*". Cambridge University Press New York, 1st edition.

Stephenson, D. A., Agapiou, J. S., 2016. "*Metal Cutting Theory and Practice*", Third Edition, CRC Press, Taylor & Francis Group, New York.

Ucun, I., Aslantas, K. and Bedir, F., 2013. "An experimental investigation of the effect of coating material on tool wear in micro milling of Inconel 718 super alloy". In *Wear,* Vol. 300, p. 8-19.

Venkatesh, V., Swain, N., Srinivas, G., Kumar, P. and Barshilia, H. C., 2016. "Review on the machining characteristics and research prospects of conventional microscale machining operations". In *Materials and Manufacturing Processes*, p. 1-28.

Wang, F., Cheng, X., Liu, Y., Yang, X. and Meng, F., 2017. "Micromilling simulation for the hard-to-cut material", In *13th Global Congress on Manufacturing and Management, GCMM 2016, Procedia Engineering,* Vol. 174, p. 693 – 699.

Wang, Z., Kovvuri, V., Araujo, A., Bacci, M., Hung, W. N. P. and Bukkapatnam, S. T. S., 2016. "Built-up-edge effects on surface deterioration in micromilling Processes". In *Journal of Manufacturing Processes,* Vol. 24, p. 321–327.

Yadav, A.Y., Kumar, M., Kajpai, V., Singh, N. K. and Singh, R., K., 2017. "Fe modeling of burr size in high- speed micro-milling of Ti6Al4V". In *Precision Engineering,* Vol. 49, p. 287–292.

Ziberov, M., Da Silva, M. B., Jackson, M. And Hung, W. N. P., 2016. "Effect of Cutting Fluid on Micromilling of Ti-6Al-4V Titanium Alloy". In *Procedia Manufacturing,* Vol. 5, p. 332–347.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.