23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

# A CONTRIBUTION TO GRINDING OF TITANIUM Ti-6Al-4VALLOY WITH VARIOUS COOLANT DELIVERY TECHNIQUES

**Antonio Vitor de Mello,**antoniovitor.82mecanica@gmail.com
**Rosemar Batista da Silva,** rsilva@mecanica.ufu.br
**Cleudes Guimarães,** profcleudes@yahoo.com.br
**Raphael Lima de Paiva,** raphaellimap@hotmail.com
**Armando Marques,** amarques@ifes.edu.br
Federal University of Uberlândia, UFU, School of Mechanical Engineering, João Naves de Ávila Avenue 2121 - Santa Mônica Campus, Uberlândia – MG. Zipcode 38408-100. Brazil.

**Rogério Valentim Gelamo,** rogelamo@gmail.com
Federal University of Triangulo Mineiro, UFTM, Institute of Technological and Exact Sciences, Dr. Randolfo Borges Junior Avenue 1250, Uberaba - MG. Zipcode 38064-200. Brazil.

**Fabio Martinho Cezar de Freitas**, fabio.freitas@saint-gobain.com
Saint-Gobain Abrasivos América do Sul, Avenida Independência, 7031, conj. 03. Vinhedo – SP. Zipcode 13280-000. Brazil.

***Abstract:*** *Most application of Ti-6Al-4V alloy is in aerospace and biomedical industries, but its application in automotive and cutting implements, like scissors and knives, for example, has also become more commonly employed. Although Ti-6Al-4V alloy is not as hard as medium carbon steel, it possesses some outstanding properties such as: it is virtually unbreakable, high strength-to-weight ratio and excellent resistance to corrosion in many environments. However, Ti-6Al-4V alloy is referred as difficult-to-cut material due to its unique combination of low thermal conductivity, high chemical reactivity with most cutting tools and rapid work hardening during machining that affect quality of the machined component. As a result of its poor thermal conductivity, heat is more concentrated in the cutting zone. This will become more critical in grinding operation, since ordinary abrasive wheels have also poor conductivity property. Then, an effective coolant delivery combined with a cutting fluid having outstanding coolant properties, as well was, geometry and positioning of jet nozzle will help to minimize heat in the cutting zone and consequently avoiding dimensional and geometrical distortions of the machined surface. Although many studies about machining of titanium at different cutting fluid delivery techniques have been related to turning and milling operations, information about grinding operation is still few. Into this context, this work presents the results of grinding Ti-6Al-4V alloy with different coolant delivery techniques as a contribution to machining field. The minimal quantity of lubrication technique (MQL) and conventional technique (flooding) were employed as well as jet nozzle positioning was varied. Two radial depth of cut values were tested. Ra surface roughness parameter was the output parameter analyzed. Images of the machined surfaces were also obtained via SEM. Results show that surface roughness is dependent on the positioning of nozzle and it increased with depth of cut. Ra values were below 0.90 µm for all the conditions investigated. Also, the best results of finishing were obtained after grinding under the combination of MQL technique and upper nozzle positioning. Occurrence of micro cracks was observed in most the machined surfaces.*

***Keywords:*** *Grinding, Ti-6Al-4V alloy, MQL technique, nozzle positioning, surface roughness.*

## 1. INTRODUCTION

Grinding is considered a finishing machining process that can provide smooth surfaces and very accurate dimensions on the machined components compared to other machining process that uses geometrically defined cutting edges like tools for turning. However, grinding is a low efficiency process since the specific energy is much larger than other metal-cutting operations, which means that a large amount of energy is used to remove a low volume of material (Malkin & Guo, 2008).The most part of the energy spent in the grinding process is dissipated into heat, which can damage the surface integrity of the workpiece. This damage can be reduced by applying a cutting fluid to remove the heat generated, and lubricate the contact between tool and workpiece so that the friction is reduced (Irani et al., 2005). Therefore, the cutting fluid plays an important role in preserving the integrity (surface and shape) of the workpiece and so it is practically indispensable in the grinding process.

Besides the type of cutting fluid used in the process, the way the fluid is applied and its flow rate are important to improve the efficiency of the fluid delivery in the process. Various papers in the grinding area can be found with the focus to seek the best alternative in the type of fluid, application mode and nozzle positioning (Irani et al., 2005; Hadad et al., 2012).

Nowadays, due to environmental appeals to reduce/eliminate cutting fluids, dry machining and Minimum Quantity of Lubricant (MQL) technique have been taking place in research as an alternative way to the use of conventional cutting fluids on grinding operations. However, compared to the conventional method, there are some issues when grinding with no cutting fluid, such as thermal damages, high grinding power and forces, high grinding wheel wear and poor surface quality (Rabiey, 2010). On the other hand, the MQL technique has shown good results on grinding, providing, in some cases, a significant improvement on cutting performance in terms of grinding wheel wear and surface finishing (Hadad and Sadeghi, 2012).

Tawakoli et al. (2010) evaluated the MQL technique efficiency for different nozzle positions and cutting fluid flow rates in the grinding of AISI 52100 (50 HRc) with aluminum oxide grinding wheel. They found that using MQL technique (50 mL/h) and the nozzle with 10° of inclination, the values of tangential force and roughness (Rz parameter) were lower when compared with the conventional application (5.3 L/min). However, despite the good lubrication that MQL technique provides to the grinding process, its cooling capability does not compare with the conventional application and for that reason, its application is still quite limited (Hadad and Sadeghi, 2012).

The position in which the cutting fluid is delivered (nozzle positioning) is an important factor in the grinding process. The correct application of cutting fluid in the contact zone can increase both lubrication and cooling capability, promoting a higher material removal. Therefore, it is important to select the best condition to deliver the fluid in the cutting zone in order to increase production and decrease costs, without affecting the workpiece quality.

When grinding titanium, the use of cutting fluid is even more necessary since burning easily occurs in this operation (Tang et al., 1990). Furthermore, Ti-6Al-4V alloy is referred as difficult-to-cut material due to some characteristics, such as chemical affinity, low elasticity modulus, low thermal conductivity, and high tendency of hardening during machining (Ezugwu and Wang, 1997). The poor machinability of Ti-6Al-4V was evaluated for conventional machining with geometrically defined tools, such as that for turning and milling, where the wear mechanism is less complex to be analyzed.

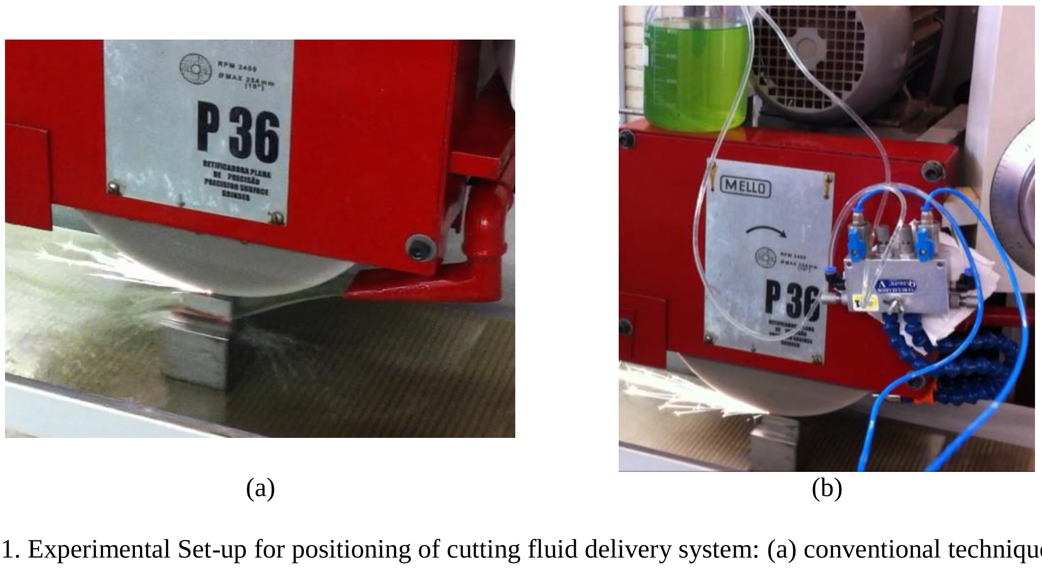
In this context, this work aims to analyze the effect of the fluid delivery system and nozzle positioning on the surface roughness of Ti-6Al-4V after grinding. SEM images of the machined surfaces were also evaluated.

## 2. MATERIALS AND METHODS

The grinding trials were carried out on a precision grinding machine, P36 MELLO, 3 HP powered and maximum speed of 2400 rpm. A white aluminum oxide grinding wheel with AA46K6V designation and dimensions of 301 mm x 25 mm x 76 mm (external diameter x width x internal diameter) was employed. The workpiece material was the aeronautical titanium alloy Ti-6Al-4V with dimensions 38 mm x17 mm x20 mm (length x width x height). The wheel ($v_s$) and workpiece speed ($v_w$) were constant for all tests and equal to 35 m/s and 6.8 m/min, respectively. For each test, 100 µm was removed from the workpiece's height through a constant depth of cut $a_e$ = 50 µm.

The abrasive wheel was dressed prior each test using a single pointed diamond dresser with a total depth of dressing equal to 50 µm: 2 passes with dressing depth ($a_d$) of 20 µm and a final pass with $a_d$ = 10 µm.

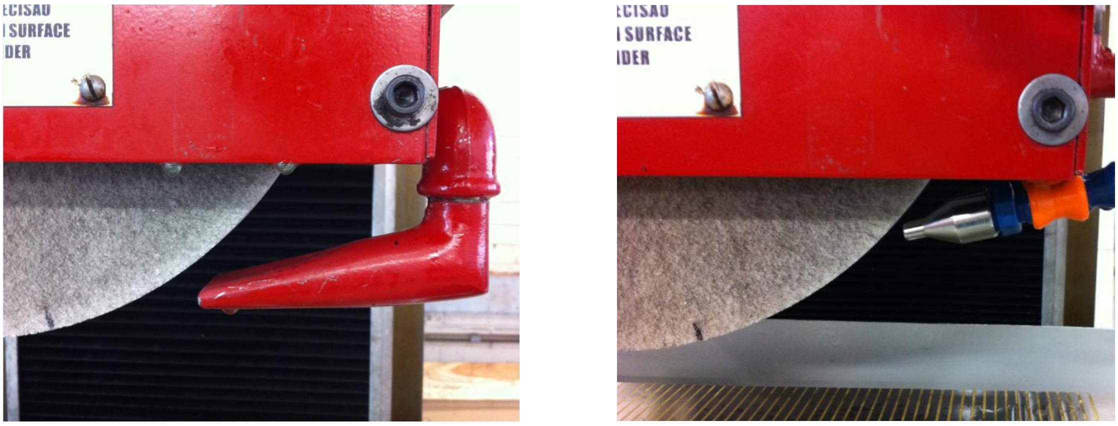
Two different cutting fluid delivery systems were tested: the conventional one at a flow rate of 755 L/h (Fig. 1a), and the Minimum Quantity of Lubrication (MQL) technique at a flow rate of 0.2 L/h (Fig 1b).




(a) (b)

Figure 1. Experimental Set-up for positioning of cutting fluid delivery system: (a) conventional technique; (b) MQL technique

The equipment used for the MQL technique was a V-type Nebulizer, from Tapmatic of Brasil Ind. and Com. Limited. Two different nozzle positions were investigated for each cutting fluid delivery system: lower and upper. In the former position, the cutting fluid is directly delivered to the workpiece, onto the surface to be machined (Fig. 2a); in the latter position, the cutting fluid is delivered on the grinding wheel surface (Fig. 2b). Combination between cutting fluid delivery technique and nozzle position resulted in four experimental machining conditions, C1 to C4, as shown in Tab. 1.



(a) (b)

Figure 2. Nozzles positioning: (a) lower positon used in conventional fluid delivery, (b) upper position for MQL technique.

Table 1. Cutting fluid delivery technique and nozzle position conditions.

| Condition | Fluid delivery technique | Nozzle position | Flow rate [L/h] |
|---|---|---|---|
| C1 | Conventional | upper | 755 |
| C2 | Conventional | lower | 755 |
| C3 | MQL | upper | 0.2 |
| C4 | MQL | lower | 0.2 |

The cutting fluid employed in all the experimental trials was a water-soluble synthetic oil, IORGA RM7 designation, at a concentration of 3%. The concentration was monitored prior to machining at each condition with aid of a refractometer model N1, Ataga, Brix 0-32%.The surface roughness parameter Ra was measured at the end of each machining condition with a portable surface roughness tester, SJ-201P model, from Mitutoyo, 0.8 mm cut-off. Four equidistant measurements were taken along the length of the machined surface and the average of measurements was calculated.

## 3. RESULTS AND DISCUSSIONS

The Figure 3 shows the results for the mean surface roughness (Ra parameter) for the tested conditions.

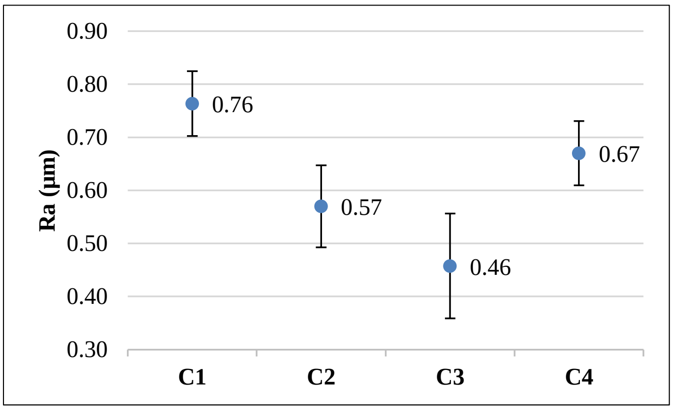



Figure 3. Surface roughness Ra values versus grinding conditions.

All Ra parameter values obtained were situated below 1.5 µm, which is considered to be the top limit for grinding process by Malkin & Guo (2008). It can be seen that both fluid delivery system and nozzle position showed significant influence on the results of surface roughness. For the conventional fluid delivery, the surface roughness was about 40% lower when the cutting fluid is directed to the workpiece surface (C2). This result can be attributed to the useful flow rate which is the amount of fluid passing through grinding zone (Malkin & Guo, 2008). If the cutting fluid is directed to the grinding wheel as it was in condition C1, the grinding wheel rotation disperses the cutting fluid, decreasing the useful flow rate and therefore, reducing the ability to lubricate and remove heat from the wheel-workpiece interface.

On the other hand, grinding with nozzle at upper position (C3) combined with the MQL technique provided lower values of surface roughness, up to 30% less compared to lower position (C4) condition. According to Klocke (2009), there is a high tendency of clogging when grinding titanium and therefore, the use of cleaning nozzle is recommended. Then, the MQL technique applied at upper position (C3) probably contributed to decrease the amount of lodged chips in the grinding wheel, improving cutting conditions.

The Figure 4 shows the machined surface aspect of the workpiece acquired with the SEM. Micro cracks were found in all samples, except for the conventional system at lower position (C2), as shown in Fig. 4b. The absence of cracks for this condition (C2) is probably due to its higher lubrication and coolant effect, since the cutting fluid is directed to the workpiece surface, increasing the useful flow rate. As can be seen in Fig. 4, the cracks on machined surface of the Ti-6Al-4V alloy propagated perpendicularly to direction to the cutting direction and it is probably a result of combined thermal, mechanical and chemical factors in the process. Such cracks can compromise the functionality of the machined surface.

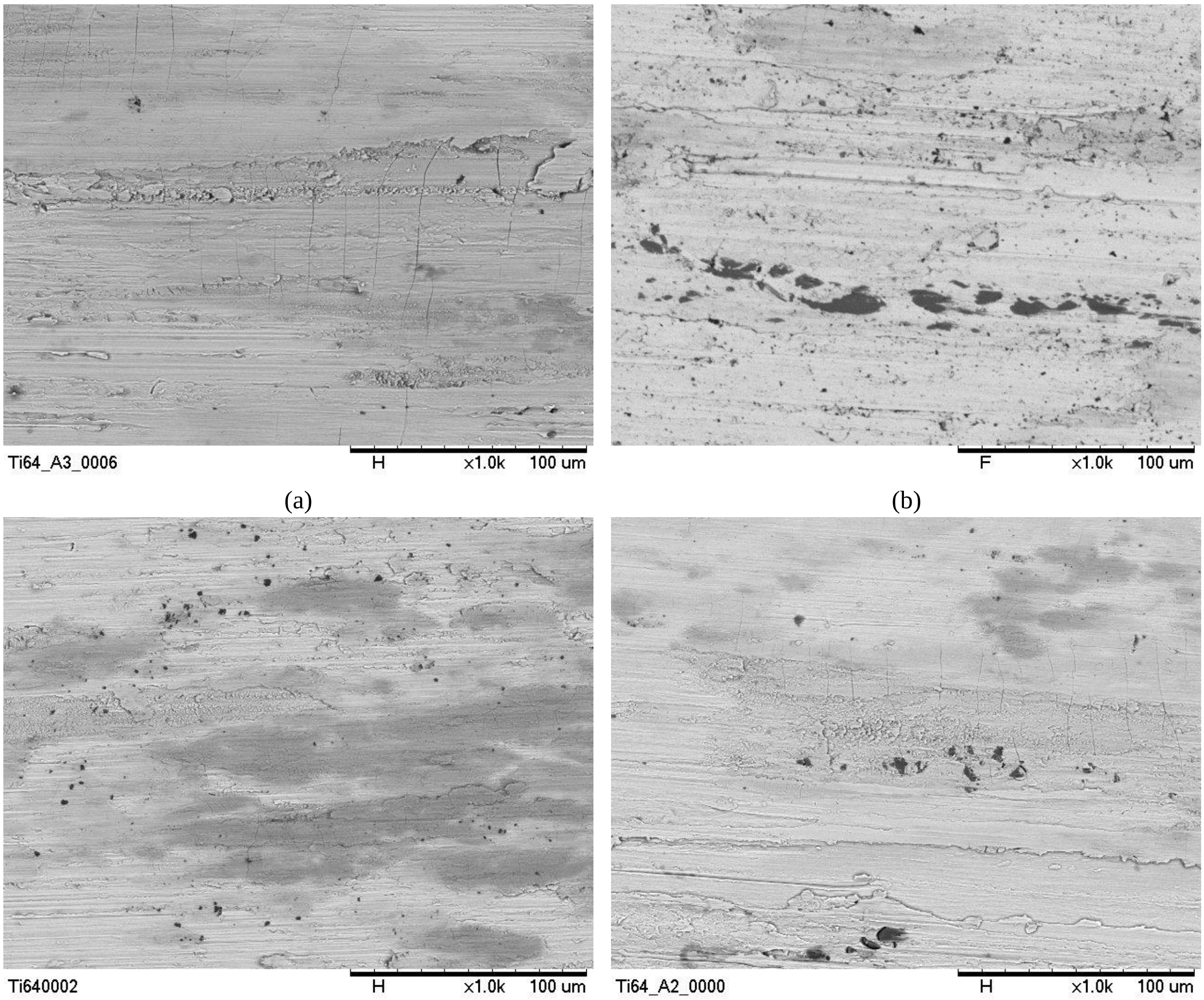



Figure 4. Ti-6Al-4V SEM images after grinding in several conditions: conventional delivery method: (a) upper and (b) lower position, MQL technique: (c) upper and (d) lower position.

Plastic deformation of the surface structures can also be seen, which can be either a result of ploughing or deposition of chips that were adhered to the grains, as it happens in Tang et al. (1990) work. They propose that stuck chips on the abrasive grains suffer a kind of coldly weld process and are detained to the machined surface and plastically deformed along the abrasive contact length. They also mention the presence of blunted grains in the surface due to increasing grinding forces. The Figure 5 shows some of the blunted (or embedded) grains found attached on the surface after machining, indicating a strong adhesive grain-workpiece reaction and/or possible high cutting forces in the conditions used in this work. According to Malkin & Guo (2008) most of difficult-to-grind metals, including titanium, are prone to exhibit more extensive cratering and grit embedding. This type of surface damage provides a source of localized stress concentrations, which can be expected to have an adverse effect on in-service strength and fatigue properties.

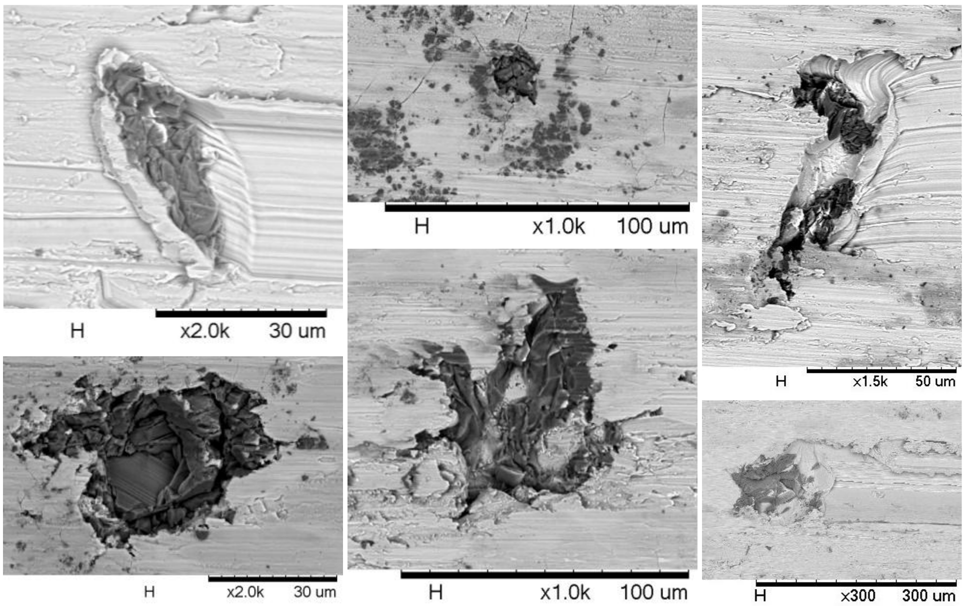



Figure 5. SEM images of blunted grains on the Ti-6Al-4V machined surfaces.

## 4. CONCLUSIONS

The following conclusions can be drawn from this work:

- The values of surface roughness are in agreement to requirements for semi-finish grinding process, which is below 1.6μm;
- Surface roughness values were very sensitive to the cooling technique employed as well as the nozzle position. In general, the best finishing was obtained after grinding with the combination of MQL technique and upper position of the nozzle;
- Micro cracks were developed on most of machined surface as result of high amount of heat concentrated at the grinding zone. Both abrasive wheel and Ti-6Al-4V alloy are poor thermal conductivity materials;
- Embedded grains were observed at the machined surface of all samples, as expected and it is in according to the literature about grinding titanium alloys.

## 5. ACKNOWLEDGEMENTS

The authors thank the Laboratory for Teaching and Research on Machining (LEPU - FEMEC –UFU) and the funding agencies CAPES and CNPq, the FAPEMIG via PPM-VII, process number: PPM-00265-13. Authors are especially thankful to the Tapmatic of Brasil Ind. and Com. Limited for the donation of the MQL equipment and also to the Saint-Gobain Abrasives of the South America for supporting this work with the abrasives tools. Some authors are also grateful the Post Graduate Program of Mechanical Engineering of Federal University of Uberlandia, CAPEX PROEX and PROPP-UFU for financial support.

## 6. REFERENCES

Ezugwu, E.G. and Wang, Z.M., 1997. “Titanium alloys and their machinability - a review”. *Journal of Materials Processing Technology*, Vol. 68, pp. 262-274.

Hadad, M. J. and Sadeghi, B., 2012. "Thermal analysis of minimum quantity lubrication-MQL grinding process". *International Journal of Machine Tools & Manufacture*, Vol. 63, p. 1–15.

Hadad, M.J., Tawakoli, T., Sadeghi, M. H., Sadeghi, B., 2012. "Temperature and energy partition in minimum quantity lubrication-MQL grinding process". *International Journal of Machine Tools & Manufacture*, Vol. 54-55, p. 10-17.

Irani, R. A., Bauer, R.J., Warkentin, A., 2005. "A review of cutting fluid application in the grinding process". *International Journal of Machine Tools & Manufacture*. Vol. 45, p. 1696-1705.

Klocke, F., 2009. *Manufacturing Processes 2 – Grinding, Honing, Lapping*. Ed. Springer, Berlin, 433 p.

Malkin, S. and Guo, C., 2008. *Grinding Technology -Theory and Applications of Machining with Abrasives*. Second Edition, Industrial Press, New York, 372 p.

Rabiey, M., 2010. *Dry Grinding with CBN Wheel, the Effect of Structuring*. Dissertation, University of Stuttgart.

Tang, J. S., Pu, X. F., Xu, H. J., Zhang, Y. Z., 1990. "Studies on Mechanisms and Improvement of Workpiece Burn During Grinding of Titanium Alloys". In *CIRP Annals*, Nanjing Aeronautical Institute/People's Republic of China, p. 353-356.

Tawakoli, T., Hadad, M. J., Sadeghi, M. H., 2010. "Influence of oil mist parameters on minimum quantity lubrication – MQL grinding process". *International Journal of Machine Tools & Manufacture*, Vol. 50, p. 521-531.

## 7. RESPONSIBILITY NOTICE

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