THE INFLUENCE OF LUBRICANT PROPERTIES IN MAGNETIC ABRASIVE FINISHING

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Abstract. *The goal of this work is to study the influence of the properties of the binding element (in this case, basic oils) added to magnetic abrasive powder over surface finish of workpieces processed by cylindrical magnetic abrasive finishing. Magnetic abrasive finishing is a recently developed manufacturing process whose objective is to provide high quality surface finishing with low material removal, at low cost. In order to evaluate the effect of the oil over the process, five different paraphinic basic oils were tested, with kinematic viscosityes at 40 °C varying from 12,8 to 487,4 cSt, and viscosity indexes varying from 219,7 (smallest temperature dependency, thinner oil) to 95,4 (highest temperature dependency,thicker oil). Also the effect of rotation speed and processing time were tested at different levels. Factorial design of experiments and three-way ANOVA were used to plan tests and analyze the results. Both oil type, rotation speed and processing time showed statistically significant effect over process, with signifficant interactions between oil type and processing time and oils tipe and rotation speed. Results strongly suggest the existance of and optimum range of viscosity, were good surface finish and high material removal are achieved with smaller processing time. This range includes oils with kinematic viscosities between 30,8 and 71,8 cSt at 40 °C. Both thinner and thicker oils showed worse results than these fluids.*

Keywords*: Magnetic abrasive finishing, Magnetic abrasive powder, Basic oil, Design of experiment, kinematic viscosity.*

1. INTRODUCTION

The goal of this work is to study the influence of lubricant characteristics, specifically viscosity and viscosity index, over roughness and material removal obtained on the processing of ironmagnetic workpieces subjected to magnetic abrasive finishing process.

Magnetic abrasive finishing is a recently developed process, whose main characteristics are the generation of fine surfaces with extremely low material removal. It is an abrasive process, whose tool is a flexible magnetic brush, composed by magnetic and abrasive powder (called magnetic abrasive powder), iron and aluminum oxide, structured by a magnetic field.

Despite its poor industrial application, Kremen et al., 1994, claimed it to be more efficient, and produce better surface finish than traditional machining processes, such as grinding, burnishing, sanding and polishing.

Magnetic abrasive finishing can efficiently achieve surface quality of the order of few nanometer on flat surfaces as well as internal and external surfaces of tube type workpieces (Jain et. al., 2001), on processes respectively called plane and cylindrical (internal an external) magnetic abrasive finishing, being also applicable on burr removal (Baron and Repkinova, 2001) and to correct geometric errors (Kremen et al., 1994).

The main process parameters on MAF are the magnetic flux density *B*, controlled by the input current on the magnet, the air gaps between magnetic poles and workpiece, cutting speed, grain size of magnetic and abrasive particles, processing time and the existence or not of mechanical vibrations.

Several studies have been done concerning the influence of the process parameters on magnetic abrasive finishing results. Jain et al, 2001, has evaluated the effect of the working gap and circumferential speed on material removal and improvement on surface finish, showing that the highest the speed and smaller the working gaps, better the surface finish. Exceptions were found for working gaps smaller than 0.5 mm, because of the restrained space, that compromises abrasive renovation. The effect of circumferential speed is related to the longer distance traveled by each abrasive particle on the workpiece surface on the same time. However, the results showed that a saturation point occurs at high speeds, and attribute this phenomenon to the accelerated wear of abrasive powder. Also processing time (Amorim et al., 2007; Amorim et al., 2006) has strong influence over surface finishing results.

The characteristics of magnetic abrasive powder have strong influence on MAF results. Important parameters include magnetic and abrasive powder type and grain size and strength of bounding between magnetic and abrasive grains. According Jain et al, 2001, there are three types of magnetic abrasive powders: bounded, loosely bounded and unbounded. While bounded MAPs have physical bounding between magnetic and abrasive particles and unbounded have no connection among different particles, loosely bounded MAPs provide weak bounding between particles, through the addition of a third material, with a binder effect. This material is, generally, a lubricant, and can be both oil and solid.

Shinmura et al., 1986, studied the impact of addition of cutting fluids over bounded magnetic abrasive powders, and found higher material removal, despite of worse surface finishing, for all studied fluids, with highest material removal associated with worse surface finishing and thicker oils. However, since tested magnetic abrasive powder was bounded MAP, the application of these results on studies concerning loosely bounded MAP must be carried out with caution.

Amorim and Lorini, 2008, compared the effect of the addition of different lubricants on MAP, over surface finishing of workpieces, finding statistically significant influence over surface finishing for lubricant and rotation speed. Three different lubricants were evaluated as binders in this work, two solid (calcium stearate and talcum powder) and one multiviscous oil. While SAE 20W40 oil allowed the obtaining of finer surface finishing at lower rotation speed (400 RPM), it showed the worst results at 800 RPM. Among the solid lubricants, talcum powder had shown the worst results, while calcium stearate allowed average surface finishing.

Previous works [Amorim and Lorini, 2008 and 2009], studied the results obtained for different lubricants, and found strong interaction between lubricant and rotation speed. For three different lubricants, it were found three different behaviors when rotation speed is increased, as shown in Fig. 1. While multipurpose low-viscosity oil allowed the obtaining of surface roughness close to 0,18 µm Ra at lower cutting speed and high-quality surface finishing at higher rotation speed and multiviscous automotive oil presented good results at 400 RPM and bad quality surface finishing at higher rotation speed, hydraulic oil allowed the generation of best surface quality at all rotation speeds.

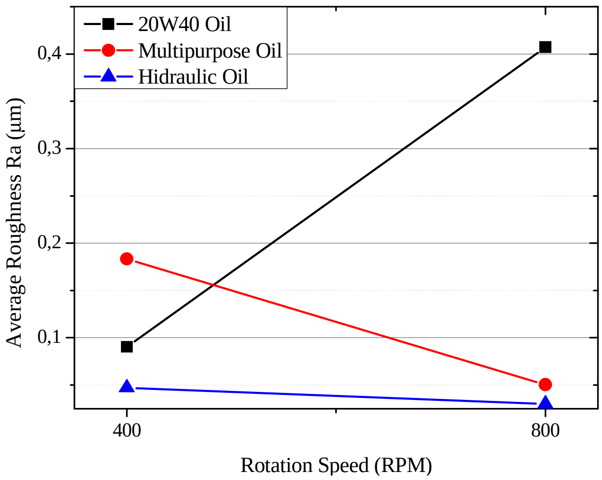


Figure 1. Surface roughness obtained by Amorim, 2008, for different oils at different rotation speeds.

Since literature shows great variation of elements and quantities added to magnetic abrasive powder as binder, and previous studies indicate strong influence of thoese elements over process results, it is of great importance to correctly evaluate the real influence of those elements over magnetic abrasive finishing results. However, despite the strength of statistical data, the utilization of commercial lubricants implies the existence of additives which can influence the results. For this reason, the objective of the present work is to evaluate the influence of the properties of the binding elements of MAP over cylindrical magnetic abrasive finishing. In order to restrain influence parameters to the viscosity of the oils, this work proposes the utilization of neutral oils, without addition of any additive.

2. Experimental procedure

For this work, several basic oils were selected, in order to reduce the influence of additives, thus limiting the study to oil properties. The tested oils were all of paraffinic type, to know: spindle 09 (PSP09), light neutral 30 (PNL30), medium neutral 55 (PNM55), heavy neutral 95 (PNP95) and bright stock 33 (PBS33), in crescent viscosity order. Table 1 shows dynamic viscosity and viscosity indexes, obtained through saybolt viscosity test, for all evaluated oils. All tests were carried out *in situs*, with the same oil samples used on magnetic abrasive powders.

Table 1. Viscosity and viscosity indexes for evaluated oils.

Tested oil	Viscosity at 40 °C (cSt)	Viscosity at 100 °C (cSt)	Viscosity index
PSP09	12,8	7,3	219,7
PNL30	30,8	9,3	178,5
PNM55	50,8	11,0	156,3
PNP95	71,8	13,1	145,6
PBS33	487,4	32,5	95,4

Figure 2 illustrates the plot of dynamic viscosity as a function of temperature for the studied oils. As shown in Tab. 1, the higher the viscosity at 40 °C, lower is the respective viscosity index, which means that, for the oils evaluated in this work, thicker oils are more affected by temperature than others. It also implicates that, as temperature increases, the difference between the viscosity of the oils is reduced.

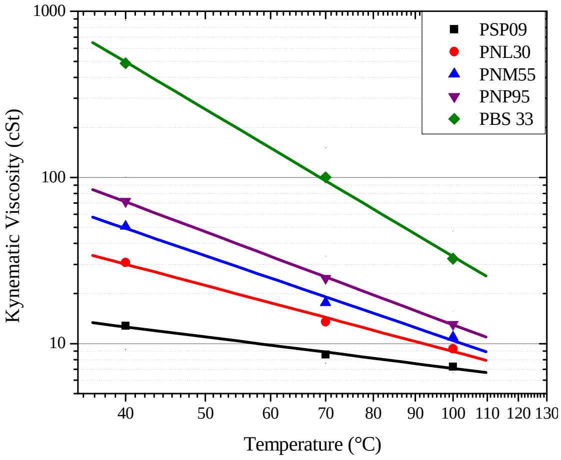


Figure 2. Viscosity as a temperature function for studied oils.

Tests were carried out on ABNT 1045 grinded bar steel workpieces, with an apparatus, composed of an electromagnet and mechanical lathe, was used to provide both magnetic field, rotation speed and vibratory motion. Test conditions are shown in Tab. 2. Magnetic abrasive powder characteristics, except lubricant type, are shown in Tab 3.

Table 2. Working conditions.

Parameter	Value
Magnetic Induction	0,65 mT
Rotation speed	400/800 RPM
Processing time	150/300 s
Working gap	1 mm
Frequency of vibration	5 Hz
Amplitude of vibration	1 mm
Workpiece material	ABNT 1045 grinded steel
Workpiece inicial roughness (Ra)	0,58 ± 0,04 µm
Diameter of the workpiece	25 mm

Table 3. Magnetic abrasive powder characteristics.

Parameter	Value
Abrasive type	Aluminum oxide
Average diameter of abrasives	88,32 µm
Magnetic particle type	Iron grit
Average diameter of magnetic particles	180,58 µm
Weight ratio ($Fe:Al_2O_3$:lubricant)	4:1:0,4

The design of experiment used for the study is a full crossed 5x2x2 factorial experiment, with three factors. The studied factors were lubricant type (5 levels), rotation speed (2 levels) and processing time (2 levels).

3. Results and discussion

Factorial design of experiments allowed experimental data to be analyzed through 3-way ANOVA (Variance Analysis). Variance analysis allows both the investigation of statistical significance of each studied factor and interactions among them.

Results of surface roughness showed statistical significant influence for both oil types, rotation speed ant processing time, in influence order. Among second level interactions, all except the one between processing time and rotation speed were found to be significant. However, third level interaction was found to be non-significant.

Figure 3 shows the results of surface roughness as a function of processing time, for both tested rotation speeds. As expected, there is a tendency of reduction on roughness with time, until a saturation point is reached. From this moment, there is no significant gain on continuing the process. The effect of rotation speed is similar: higher speeds allow more material removal in smaller processing times. An indicative of this effect is that results of testes carried out at 800 RPM for 150 s showed no statistically significant difference from results obtained at 400 RPM for 300 s, which is expected, since the effective cutting length is the same. These results agree with those obtained by Jain et al., 2001, which suggested that the improvement on surface finishing obtained at higher cutting speeds is due to the increase of the length travelled by the abrasives over workpiece surface.

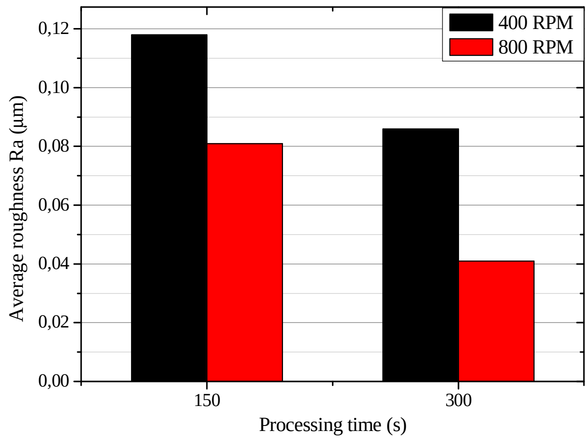


Figure 3. Surface roughness obtained after different processing times.

Figure 4 presents results of surface finish obtained through the use of different oils. Thinner oil (paraffinic spindle 09) presents the worst results, followed by PBS 33. Multiple average comparisons didn't show any significant difference between PNL 30, PNM 55 and PNP 95 oils. Those results indicate a range of viscosities were the best surface finishing is obtained.

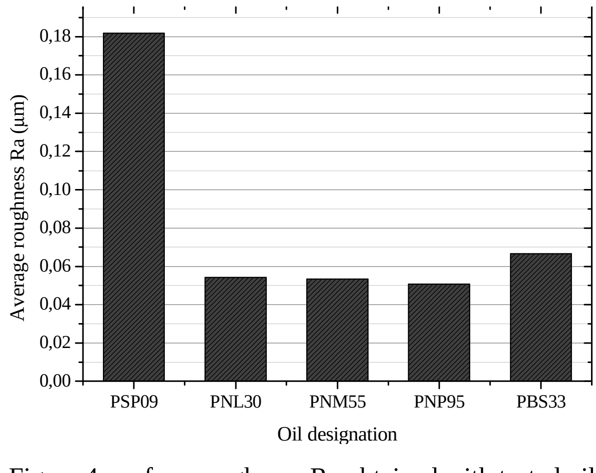
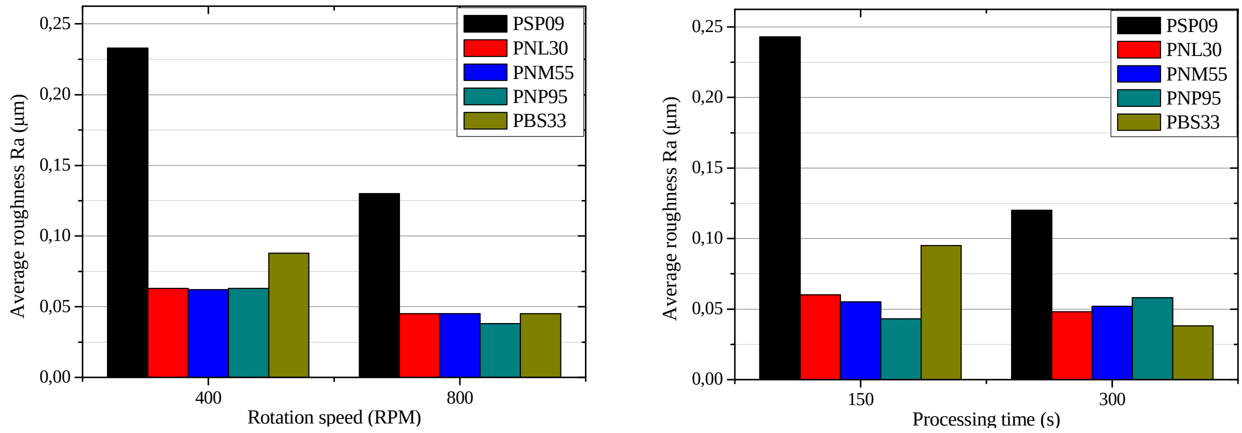


Figure 4. surface roughness Ra obtained with tested oils.

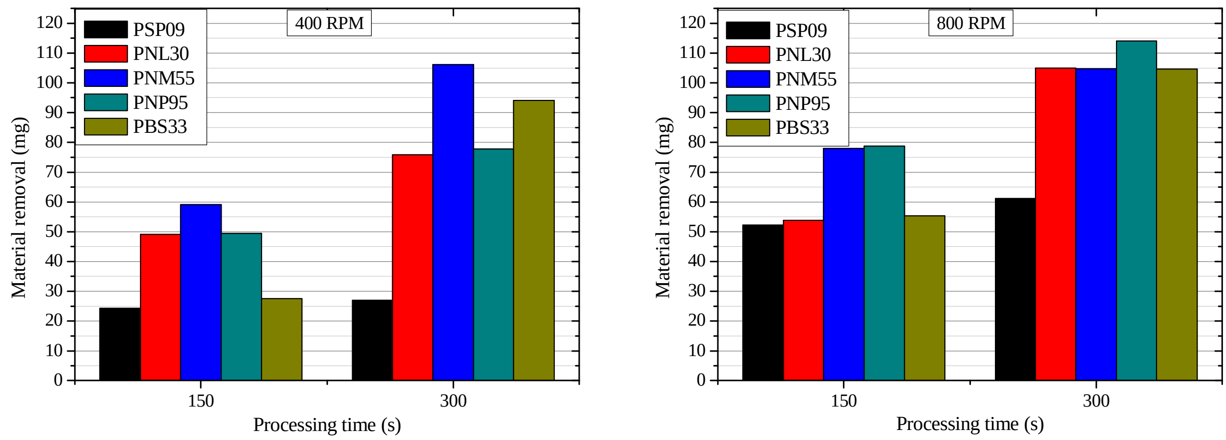
Figure 5 (a) and (b) presents three factor plots for the results of surface roughness obtained using the different oils, as a function, respectively, of rotation speed and processing time. It is clear, for both PSP09 and PBS33 oils that both factors improve surface finish. However, while higher rotation speed causes small improvement on the other oils (PNL30, PNM55 and PNP95), the increase of processing time had caused no significant difference for these products, with occurrence of worse (but not statistically significant worse) surface finishing after 300 s than at 150 s. An important result not showed in this plot is the individual results of PSP09, processed for 300 s at 800 RPM. The results for this condition were on same range of results obtained for PNL30 to PNP95 at 800 RPM for 150 s, indicating that, under tested conditions, and concerning Ra average roughness only, type of lubricant solely has influence over the velocity of the process, but not over the saturation point.



(a) (b)

Figure 5. Variation of surface roughness for different oils as a function of: (a) rotation speed; and (b) processing time.

Figure 6 (a) and (b) show material removal as function of time for tested oils at 400 and 800 RPM. Surprisingly, material removal doesn’t seem to be directly related to viscosity, since highest material removal at 400 RPM was obtained with PNM55, whose kinematic viscosity at 40 °C is between PNL30 and PNP 95 viscosities. Probable reason for this behavior is the existence of an “optimum range” for oil viscosity, were the bounding force caused by the lubricant is strong enough for the abrasives to cut, but still allows their renovation on the cutting zone. As expected, PSP09 oil provided small amounts of material removal, both at 400 and 800 RPM, due to the weaker bounding between magnetic and abrasive particles. However, the unexpected result is that, while the use of PBS33 oil allowed low material removal after processing for 150 s, it provided high material removal after 300 s, when compared to the other basic oils. This phenomenon can be related to the temperature in the cutting zone. Since this oil has low viscosity index, i.e., it is strongly affected by temperature, higher processing time allows the obtaining of higher temperatures, thus reducing bounding strength due to viscosity, thus allowing abrasive renovation.



(a) (b)

Figure 6. Material removal for magnetic abrasive powders containing different oils at (a) 400 RPM; and (b) 800 RPM.

Relationship between material removal and surface finishing can be observed through comparison of figure 6 (a) and (b) with figure 7 (a) and (b), which present surface roughness as a function of processing time for each individual test. This comparison indicates a strong correlation between those response parameters, with high material removal associated with good surface finishing. These results disagree with the observed by Shinmura et al., 1984, where high material removal was associated with worse surface finishing. This apparent discrepancy indicates a fundamental difference between magnetic abrasive finishing with bonded and weakly bounded magnetic abrasive powder. While in the former magnetic and abrasive particles are physically bounded through chemical or physical process, such as sintering, preventing abrasive rotation and so allowing higher cutting forces, weakly bounded MAPs impose weaker resistance to abrasive rotation. Thus, the cutting force and, consequently, material removal is higher using bounded MAP, which indicates that the different behavior relating roughness and material removal in this case is due to the process occur after the wear of roughness peaks, while the use of unbounded MAPs causes progressive removal of those structures, and so gradual improvement on surface finish.

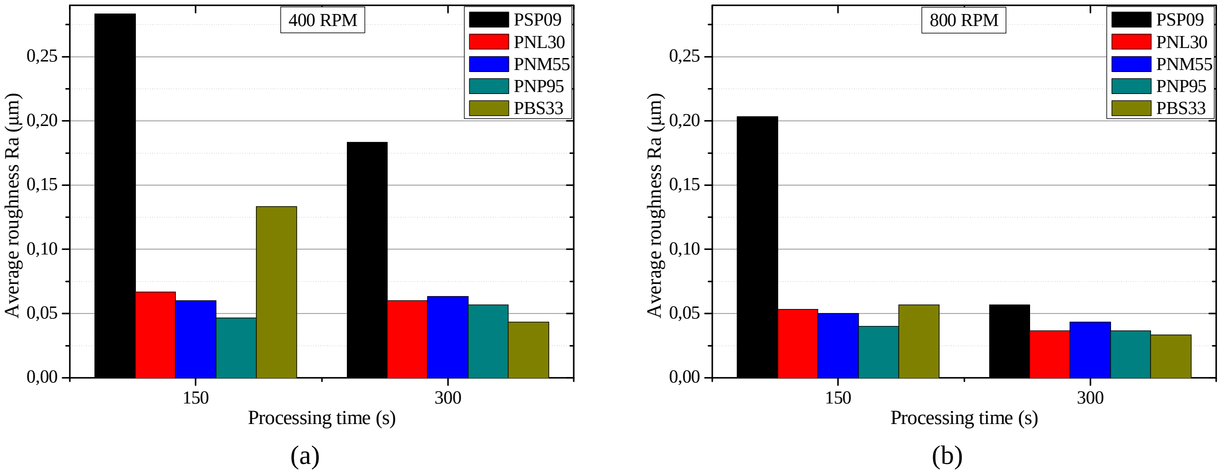


Figure 7. Average roughness obtained for magnetic abrasive powders containing different oils at (a) 400 RPM; and (b) 800 RPM.

Material removal obtained through execution of magnetic abrasive finishing at 800 RPM shows results very similar to obtained at 400 RPM. In fact, there was observed, for some oils, few or no difference between both speeds, which indicates that, for these combinations of element/parameters (PNL30 oil/150 s; PNM55 oil/ 300 s), the positive effect of higher cutting length over material removal is partially compensated by dynamic behavior, thus resulting on a saturation point. It is also evident that, despite both processing time and rotation speed have equivalent effect over surface finishing, material removal is more affected by the former, as can be seen by comparison between the results obtained after 300 s at 400 RPM and after 150 s at 800 RPM, figure 7 (a) and (b). Exceptions were seen for PSP09, which allowed higher material removal at the second condition, and PNP95, which provided results barely different.

The effect described by Amorim, 2009, and showed in Fig. 1 was not observed. Since it occurred with multiviscous automotive oil, it can be related to the high amount of additives, which can, in this case, cause a specific non-newtonian behavior called pseudoplastic. Pseudoplastic behavior makes apparent viscosity to decrease at high shearing rates. Once shearing rate increases with the relative speed between surfaces, this phenomenon tends to occur at high cutting speed.

Figure 8 shows a workpiece obtained after machining with magnetic abrasive finishing for 300 s, using magnetic abrasive powder with addition of PNM55 oil. It is possible to distinguish the quality of the surface finish through the reflection of the letters over the region were magnetic abrasive finishing process was applied, especially when compared with the grinded part of the workpiece

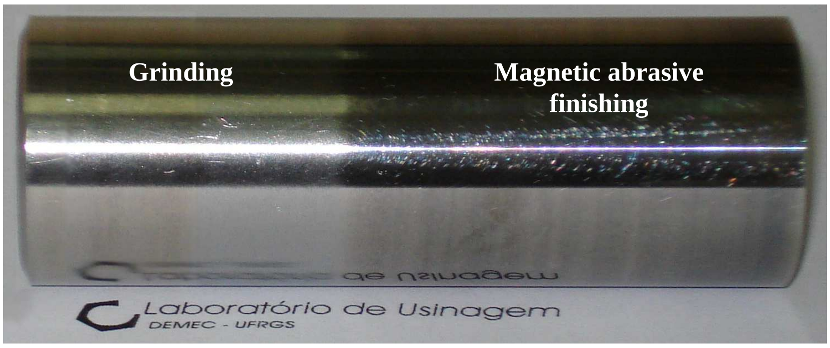


Figure 8. Surface quality obtained through grinding and magnetic abrasive finishing.

3. Conclusions

Through careful analysis of experimental data, it is possible to reach important conclusions concerning the properties of the oils used as binder for magnetic abrasive powder, as well as to confirm the influence of well documented process parameters, such as rotation speed and processing time.

Both higher and lower viscosity oils presented worse surface finish at evaluated processing time, which indicates the existence of an ideal viscosity range. Probable cause is the bonding force between magnetic and abrasive particles, which increases with higher viscosities. Thus, while PSP09 oil provides weaker bounding force, what increases processing time for providing fine surface finishing and high material removal, PBS33, due to excessive bonding, restrains the abrasive particle renovation in the cutting zone. This effect is reduced after longer machining intervals, when PBS33 allows high material removal and good surface finishing.

Under the tested conditions, a relationship exists amongst surface finish and material removed through magnetic abrasive finishing process, which relates low surface roughness with high amounts of material removal. This relation

Optimal range of viscosity is indicated by behavior shown in Fig.4-7, were PNL30, PNM55 and PNP95 oils allowed achievement of both good surface finish and high material removal.

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