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Effects of different cutting strategies on G-ratio in through-feed center-less grinding

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ABSTRACT. Grinding is the main manufacturing process used in finishing operations. Center-less grinding is widely used in the production of auto parts e.g. roller bearings, valve stem and stem of shock absorbers. Center-less grinding is used in large-scale production due to shorter time and higher flexibility. However, the set-up of the grinder is complex and slow, and depends on the operators' ability. The choice of the best parameters in the process is important to define exactly the cutting strategy and to optimize the process. Current study analyzes the input parameters: feed rate and type of materials on the responses G-ratio, surface roughness, and roundness. Thus, stems of shock absorbers were used as work pieces on the shop floor. Cutting speed and grinding wheel type were constant. The input parameters comprised feed rate and type of materials (1025 and 1045). Responses were surface roughness, roundness error and G-ratio. Results demonstrated that the kinds of tested material was the parameter that most influenced G-ratio and surface roughness. Moreover, feed rate had little influence on the quality of the work pieces, mainly on roundness error.

Keywords: center-less grinding, G-ratio, surface roughness, cutting speed.

Efeito das diferentes estratégias de corte sobre o fator-G na retificação sem centros de passagem

RESUMO. Retificação é o principal processo usado em operações de acabamento. Especificamente, retificação sem centros é largamente usada na produção de autopeças como, por exemplo, mancais de rolamentos, hastes de válvulas e hastes de amortecedores. Retificação sem centros é usada em produção de larga escala pelo baixo tempo e alta flexibilidade. Entretanto, o *set-up* da retificadora é complexo, lento e depende da habilidade dos operadores. Portanto, a melhor escolha dos parâmetros no processo é importante para definir exatamente a estratégia de corte e permitir a otimização do processo. Este artigo mostra a análise dos parâmetros de entrada; taxa de alimentação e tipo de material nas respostas fator-G, rugosidade e circularidade. Assim, hastes de amortecedores foram usadas como peças de trabalho no chão de fábrica. A velocidade de corte e o tipo de rebolo foram mantidos constantes. Os parâmetros de entrada foram a taxa de alimentação e o tipo de material (aço SAE 1025 e 1045). As respostas foram a rugosidade, o erro de circularidade e o fator-G. Os resultados demostraram que o tipo de material testado foi o parâmetro que mais teve influência sobre o fator-G e a rugosidade. Além disso, a taxa de alimentação teve pequena influência sobre o acabamento das peças de trabalho, principalmente no erro de circularidade.

Palavras-chave: retificação sem centros, fator-G, rugosidade, velocidade de corte.

Introduction

Preparation of center-less grinding machines is highly complex and demand several proceedings to provide perfect conditioning and smooth grinding. Prior to the start of the production of parts, dressing and cleaning are the main activities developed in the preparation of the grinding wheel. The dressing operation aims at cleaning, sharpening, and truing the grinding wheel (Wegener et al., 2011).

It is essential that a setup is prepared to support the work piece and control its rotational motion during the center-less grinding. The installation of a grinder on the surface grinder work table is very important to ensure a stout process without great changes in the setup of input parameters (Wu, Kondo, & Kato, 2005).

Mechanical, thermal and chemical loads are present during the grinding process and are applied to the grinding wheel. The main effect of these loads is the wear that modifies the topography of the tool. Macro-wear occurs by providing the deterioration of macro-geometry in the changing of the profile, provoking size errors and run out. Moreover, micro-wear occurs in the meantime and may be divided into two different situations, such as the pull-out that corresponds to the complete clearance of grits, and the break-off of the grits that provide new cutting edges (Klocke & König, 2005).

These phenomena occur simultaneously and are correlated to the parameters of process, kind of material, and dressing operation. The dressing operation resets the topography and improves the quality of the grinding wheel. The dressing operation provides low wear of grinding wheel and does not affect its consumption.

The grinding wheel's consumption is called G-ratio and corresponds to the cubic volume of stock removed divided by the cubic volume of grinding wheel wear. The G-ratio is influenced by the hardness of the material of the work piece, and the type of grinding wheel. Generally, low-hardness materials are machined with hard-grinding wheels whereas the opposite situation occurs with hard materials, such as super abrasives grinding wheels. Taking the traditional grinding process into consideration, the ratio ranges between 20:1 and 80:1 (Bianchi, Aguiar, Monici, Daré Neto, & Silva, 2003).

G-ratio is affected by several parameters during the grinding process, mainly in through-feed center-less grinding. Despite their poor cooling properties, cutting oils are commonly used at low speed to decrease the consumption of grinding wheels. The performance of grinding improves with the use of cutting oils. The authors tested 45 different types of metalworking fluids and showed that they achieved up to 10 times higher the G-ratios when compared to water-soluble oils (Yoon & Krueger, 1999).

Cutting forces are another important factor that changes the G-ratio acting in parallel with cutting oils. The application of oils enriched with a high concentration of MoS_2 at 5 mL min^{-1}, may reduce the grinding forces by approximately 27% and increase G-ratio by 46% over flood cooling (Shen, Malshe, Kalita, & Shih, 2008).

Several authors have proposed quite a lot of methodologies to optimize the grinding process. Some techniques generate a number of solutions for each of the input parameters, such as material properties, grinding wheel parameters, work-piece speed, in-feed and dressing condition. According to the authors, the in-feed is the most promising variable because it has a direct interference on G-ratio, grinding time and surface quality (Gupta, Shishodia, & Sekhon, 1999; Rascalha, Brandão, & Ribeiro Filho, 2013).

G-ratio may range between 31.7 and 52.3, depending on the setup of the in-feed in the grinding process. Furthermore, the hardness of the work-pieces greatly influences G-ratio because the pull out, burn and/or the breakage of grains is directly related to the load on the grains and the grinding wheel structure (Midha, Zhu, & Trmal, 1991).

Information on G-ratio is very important on the shop floor due to the high costs involved in grinding, mainly in the through-feed center-less grinding that is a process with high production rates. Thus, current study shows the influence of the input parameters; feed rate and kind of materials on the responses G-ratio, surface roughness, and roundness. Two materials, 1025 and 1045, were used as work-pieces in the through-feed center-less grinding.

Methodology

Tests were carried out on the shop floor of a manufacturer of shock absorbers. The machine tool used was a center-less grinding model Twin Grip 350-20 RK with 50 HP of main motor power manufactured by Cincinnati. Oil emulsion EcoCool P1978 was supplied by FUCHS™. Flow rate of oil emulsion was 130 L min^{-1}, and concentration ranged between 6 and 8%.

A grinding wheel ART AA80 KVS with external diameter 609.6 mm, internal diameter 304.8, and 508 mm long, was applied in experimental tests with cutting speed of 40 m sec^{-1}. Input parameters were types of material and two feed rates. The interaction between input parameters generated four experimental tests with three replicates. The depth of cut was maintained constant at 0.27 mm. Table 1 shows the main characteristics of the work pieces.

Table 1. Technical specification of work pieces.

Material	Chemical composition [%]					Grain size	HRA
	C	Mn	Si	P	S		
ABNT 1045	0,45	0.50	0.15	0.045	0.045	5-8	75
ABNT 1025	0.25	0.45	-	0.04	0.05	5-8	68

The work pieces had a diameter ranging between 12.4 and 12.425 ± 0.005 mm and a length between 289 and 380 ± 0.3 mm, with a hardened surface layer of 0.5 - 1 mm thickness. The number of work pieces manufactured was 3.342.656, and the grinding wheel was used until its end life. The mean consumption time of a grinding wheel is 29 days for rough grinding and 49 days for finishing grinding processes. The experimental tests were carried out on shop floor with rough grinding wheel and tests were replicated three times to ensure data rates.

The surface roughness was measured at three points opposed 120° with a digital device Mahr Perthometer, model M2 Werk. The surface roughness was measured in five work pieces chosen randomly at each hour. A three-dimensional measuring machine, model Zeiss Condura G32, measured the cylindrical form of work pieces by the same strategy of surface roughness. Table 2 shows input parameters with their levels.

Table 2. Levels of the input parameters.

Input parameters	Levels	
	-1	1
Feed rate	4.3m min^{-1}	6.1m min^{-1}
Material	ABNT 1025	ABNT 1045

Responses comprised surface roughness, circularity and G-ratio. G-ratio was measured by cubic volume consumed from stock removed divided by the cubic volume consumed from grinding wheel wear. The cubic volume of stock removal was calculated by measuring the dimensions of stem before and after the grinding process and multiplied by the number of stem produced.

The cubic volume of the grinding wheel was measured with the displacement of the dresser, which controls the diameter of the grinding wheel. The experimental tests in measuring were performed at the environmental temperature of 26°C.

Experimental design was carried out to optimize tests, whilst MiniTAB™ software verified main factors and interactions.

Results and discussion

Main effects

P-values (0.000 and 0.042) underlined in Table 3 show that the main effects "Material" is significant for G-ratio and surface roughness which, unlike feed rate and material, are not significant for roundness error. The adjusted R^2 rates were 78.07, 74.57 and 88.32%, and indicated the adjustment quality of the model. Figures 1, 2 and 3 show the main effect plot for the G-ratio, surface roughness and roundness error.

Figure 1 shows the effect of the feed rate (A) and material (B) on G-ratio, presenting a 29.6% variation between the material types 1025 and 1045. The above behavior may be explained by the hardness of 1045 when compared to 1025. Hard materials such as 1045 with hardened surface layer generally provide a break off of the grits instead of the pull out of the grits.

This condition is important because it provides a lower rate of consumption of the grinding wheel and generates sharpening of the grinding wheel. Moreover, a 9.25 G-ratio is a good rate for center-less grinding process, when the great volume of production available for the grinding process is taken into account.

Table 3. Analysis of variance (P-values).

Experimental factors	G-Ratio	Surface Roughness [μm]	Roundness Error [μm]
	Mean effects		
Feed rate	0.800	0.444	0.543
Material	0.000	0.042	0.918
	Interaction plots		
Feed rate * Material	0.712	0.753	0.258
R^2 Adjust (%)	78.07	74.57	88.32

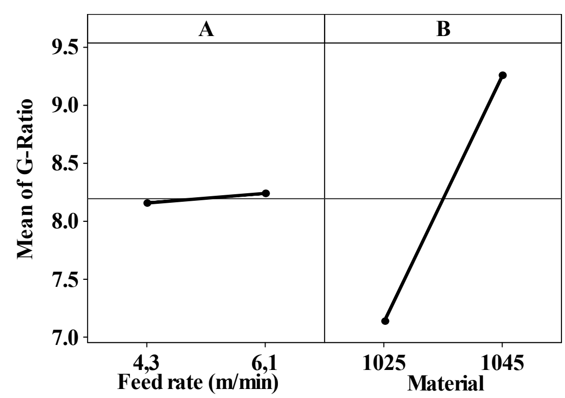

Figure 1. Main effect plot for G-Ratio.

Figure 2 shows the effects of the feed rate (A) and material (B) on the surface roughness, and presents a low variation of only 7% between feed rate of 4.3 and 6.1 m min^{-1}, and a variation of 22% between the material type 1025 and 1045. The above behavior may be explained by the high hardness of 1045 that provides the break off grits and generates the best finishing of work pieces due to sharpening of grits.

According to the data sheet of the grinding wheel, the structure number was 60 and featured an open structure. Generally, grinding wheels with open structures maintain the grits away, avoiding the pull out of the grits due to their rigid fixing. The structure helps the friability of grinding wheel, or rather, the ability of abrasive grits to fracture and self-sharpen under stress.

Therefore, it may be presumed that the kind of material 1045 changes the break off grits and improves its friability. Thus, the cutting mechanism of grinding wheel becomes more efficient with less stress on the grits. Therefore, G-ratio and grinding wheel life increase with change of the costs and the efficiency of the grinding process.

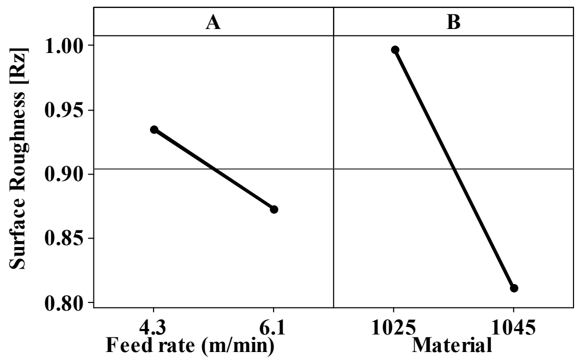

Figure. 2 Main effect plot for surface roughness.

The break off grits provides thinner scratches and minimizes the ploughing effect due to more accurate surface roughness. Ploughing effect occurs during grinding when dull grains push into the work piece without cutting it. The grinding process is composed of three actions, namely, cutting, rubbing, and ploughing, the contribution of each being highly affected by grit geometry. The specific energy in rubbing or ploughing is more than that required in cutting or chip formation. Thus, decrease of surface roughness occurs not only due to the break off grits that generate thinner scratches but also to the low specific energy spent during the grinding process.

The 7% decrease of roughness surface due to the increase of feed rate corresponds to the quick displacement of the stem into the grinding gap producing a cutback of the number of scratches and an improvement of roughness surface.

Figure 3 shows the effects of the feed rate (A) and material (B) on the roundness error, with a 5% variation between the feed rate of 4.3 and 6.3 m min^{-1}, and a small variation of 0.9% between the material types 1025 and 1045. Although the feed rate and material showed variations on the roundness error with a decrease for both input parameters, the rates may be negligible. It may be thus presumed that feed rate and material have no influence on the roundness error.

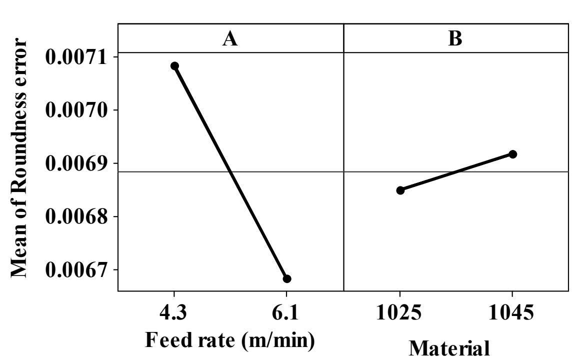

Figure 3. Main effect plot for surface roughness.

Interaction plots

Figure 4 presents the interaction effect plot of “feed rate and material”. The change of material type from 1025 to 1045 provided a 31% average increase of G-ratio. The result of interaction effect plot confirms that the great hardness of 1045 provides the best break off grits with a decrease of the grinding wheel wear. Moreover, the feed rate showed a similar behavior with parallel lines, with no interaction of material on feed rate into G-ratio.

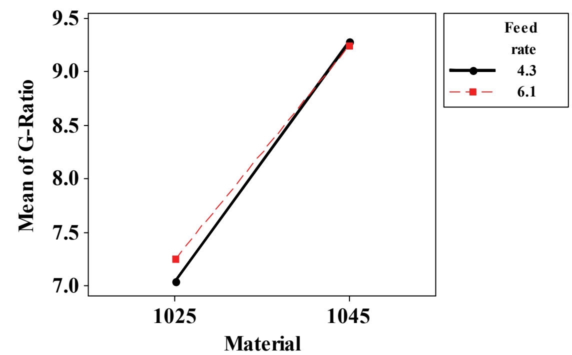

Figure. 4 Interaction plot for G-ratio

Figure 5 shows the interaction effect plot of “feed rate and material” with surface roughness. A decrease of surface roughness when 1045 was manufactured may be observed. Decrease rate was similar whether it was 25% to 1045 and 20% to 1025 and demonstrated no interaction between feed rate and material. The decrease of surface roughness represents an improvement of finishing of stem and demonstrated that the 1045 provided a better finishing than 1025.

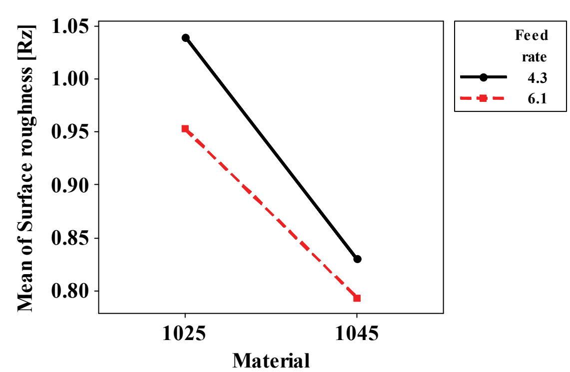

Figure 5. Interaction plot for surface roughness.

Figure 6 presents the interaction effect plot of “feed rate and material” into roundness error. A decrease of roundness error may be observed from 1025 to 1045 for the feed rate of 4.3 m min^{-1}. In an opposite situation, increase occurred in the feed rate of 6.1 m min^{-1}. It may thus be presumed that the effect of feed rate depends on the material and demonstrates that there is an interaction between the input parameters.

However, as commented above, although there is an interaction between the parameters, Figure 6 reveals that feed rate and material have no influence on the roundness error. It may be presumed that decrease of roundness error is independent of the variation of feed rate and kind of material.

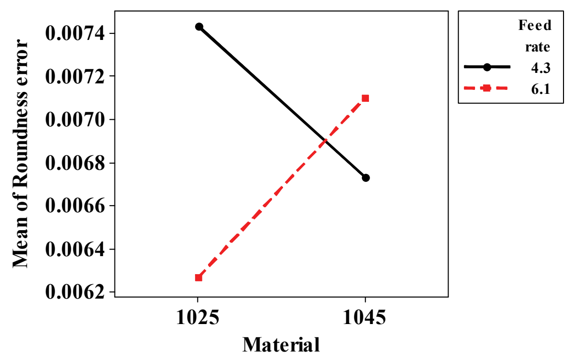

Figure 6 Interaction plot for roundness error.

Conclusion

Current study pointed out the effects of feed rate and material on the G-ratio, surface roughness, and roundness error. The main conclusions of the analysis are:

Change of material type from 1025 to 1045 increases G-ratio. The G-ratio rate 9.25 represents a good index when the through-feed center-less grinding is a process with high productive rate and great grinding wheel wear is taken into account.

Decrease of surface roughness occurred with the change of material type from 1025 to 1045. The decrease of surface roughness was 22% with the change of material. Increase of feed rate was less significant and represented 7% in the decrease of surface roughness.

The variation of feed rate and type of material does not affect roundness error. The variation of roundness error was 5% for the increase of feed rate and a small variation of 0.9% for the type of material.

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