1º COBEF
Congresso Brasileiro de Engenharia de Fabricação
02 a 04 de abril de 2001 • Curitiba - Paraná - Brasil

THE CUTTING FLUID INFLUENCE IN THE INLET ENGINE VALVES GRINDING

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Abstract. *In this paper is presented an experimental research in which the grinding of inlet engine valves was improved by the adoption of the most effective cutting fluid type, matching the new requirements of cutting fluid application. Four different types of cutting fluids (cutting oil and three different types of soluble oils) were analyzed. As evaluation parameters of the performance of the cutting fluids, the roughness, the grinding wheel wear and the workpiece residual stress were measured. As a conclusion, the cutting oil is the most adequate cutting fluid to be used, due to its tendency in reducing the roughness, the wheel wear, due to its higher lubricity and ability in keeping the wheel sharp for longer periods of time. The main factor of choice was the compressive residual stress generated during all grinding cycles by this type of cutting fluid, which can increase the fatigue life and the mechanical proprieties of the ground component.*

Keywords**:** *Cutting fluid, Grinding, Valves, Residual stress*

1. INTRODUCTION

Fluid application in grinding process is becoming more important as higher stock-removal rates, higher quality, and longer wheel life are sought. Selection of an efficient way to apply it, and straight follow the standard procedures of cutting fluid maintenance are extremely important to meet productivity goals and can be as important as selection of the grinding wheel specification (Webster, 1995).

The conventional method of grinding fluid application is in the form of flood through a remote nozzle. Most often, this method of flood application is not very effective, specially under severe grinding conditions, as the energy of the fluid is not sufficient to overcome the centrifugal force of the wheel or to penetrate the boundary layer of air surrounding the wheel. Consequently, only 5% to 30% of the cutting fluid is effectively used in conventional flood application in grinding operation (Guo & Malkin, 1992). As a result of the non-effective cooling and poor lubricity in the interface wheel-workpiece, there is an increase in the number of wheel dressing. Consequently, the frequent resharpen causes a premature failure of the grinding wheel, because about 90% of the wheel material is lost during dressing and only about 10% of the wheel is consumed during grinding, making the process highly uneconomical and inefficient. This dressing process also leads to grinding interruptions, machine down-time and additional setup time (Kovacevic & Mohan, 1995).

According to Webster (1999), fluid application that does not take the advantage of the wheel ability to act as a pump (Guo & Malkin, 1992) will cause high contact arc temperatures up to the point when the fluid quenches the bulk material just after the wheel has passed by. This post grinding quenching can create undesirable tensile stress in the workpiece surface and can also overheat the wheel bond and abrasive materials. Consequently, the optimization of the grinding process implies not only the selection of the right grinding wheel and cutting parameters but also the adoption of the most effective grinding fluid and its correct way of application.

This paper presents a comparative study in which a inlet engine valves grinding operation was improved by the adoption of the most effective cutting fluid type, among four different ones. Qualitative and quantitative grinding outlet parameters, such as: roughness, radial wheel wear and residual stress, were analyzed in order to determine the most adequate cutting fluid to be used. The fluid application was improved in order to follow the new requirements of jet coherence and jet velocity (Webster, 1995, 1999).

2. CUTTING FLUIDS: CLASSIFICATION, FUNCTIONS AND ASPECTS THAT AFFECT THEIR PERFORMANCE

2.1 Classification

Each of the basic types of fluids has distinct features, advantages and limitations, although the dividing line is not always clearly identifiable (Motta & Machado, 1995). According to ASM (1991), the cutting fluids can be divided in two basic groups:

Cutting oils: they have a mineral oil base and may be used straight (uncompounded) or compounded (combined with polar additives and/or chemically active or inactive additives or compounds). The cutting oils have excellent lubrication properties, good rust control and long life, but they don’t cool as well as water-miscible fluids.

The **water-miscible fluids:** they are mixed with water at different ratios depending on the machining operation. They can be classified as emulsions (emulsifiable oils) or synthetics depending on the basic formulation of the concentrate of the cutting fluid (mineral oil or chemical agents, respectively). Blending with water, the water-miscible fluids provide the combined cooling and moderate lubrication required by metal removal operations conducted at high speeds and lower pressures.

2.2 The roles played by the cutting fluid in grinding

To be really effective therefore, a coolant should not only provide good convective cooling of the workpiece but also promote cutting as opposed to plowing. As a result, there is a decrease in the grinding specific energy required in the process (Malkin, 1989).

The cutting fluid can lead to cutting instead of plowing by two different ways (Hitchiner, 1990): making the wheel sharp - the coolant can act to inhibit glazing and capping of the grits by the decrease of the coefficient of friction; reducing the coefficient of friction - lowering the coefficient of friction between grit and workpiece allows blunter grits to cut, as well as reducing overall forces levels for a given stock removal rate. This brings a double benefit: the energy to be dissipated is lowered, and because cutting is favored, it is more easily dissipated.

According to Carius (1989) cited by Webster (1995), in almost all cases wheel wear is reduced by using cutting oils. Their higher lubricity, as compared to soluble oil, gives rise to lower specific energies, resulting in the reduction in specific energy and rate of growth of wear flats on the grits. It would thus seem possible that cutting oil could also produce lower values of specific energies than soluble oils in creep-feed grinding and so possibly outweigh the disadvantage of its lower values of critical power flux.

Hard steel components are probably better ground with a cutting oil than with a water-soluble fluid. The heat treatment used to harden them is liable to leave them in a state of tensile stress, especially thick sections, so relatively small grinding stress will often induce to catastrophic cracking and the high-quenched rates found with synthetics are a disadvantage. Avoidance of burn is better achieved by good lubrication, which will reduce grinding forces and promote cool cutting. With softer, more ductile components, emulsion or synthetics fluids may be useful. High quench rates can be tolerated without cracking, and higher temperatures must be reached before burn occurrence.

2.3 The aspects that influence on the performance of cutting fluids used in grinding

Grinding fluids are traditionally used as an external means to improve the process performance by providing lubrication and cooling at the wheel-workpiece interface. However, the effectiveness of the grinding fluid depends upon many factors, such as the location of placement, flow velocity, quantity of flow, direction of application, the design of the nozzle, among others. Within the grinding zone, convective cooling by grinding fluid can usually be neglected in regular grinding due to film boiling (Lavine & Malkin, 1990).

The film boiling phenomenon affects water-soluble fluids and cutting oils in a different way (Yasui & Tsukuda, 1983). As reported by the authors, the occurrence of the film boiling in water-soluble fluids lowers the heat transfer coefficient of the fluid to almost the same as air. As a result, the cooling performance in these fluids deteriorates to become almost the same as in dry. Since the physical properties of water-soluble fluids are almost the same as water, the film boiling seems to occur at the temperature in slight excess of 100 ^{o}C. On the contrary, the cutting oil is a mixture of different oils having different boiling temperature and its average boiling point is about 300 ^{o}C. Therefore, at a rougher grinding conditions, the effect of film boiling is more critical when a water-soluble fluid is applied.

The use of CBN grinding wheels can lead to reduce the film boiling occurrence. It was found by Kohli *et al.* (1995) that 60-75 percent of the grinding energy is transported to the workpiece as heat with an aluminum oxide abrasive wheel, as compared to only 20% with CBN wheels. An analysis of the results indicates that the much lower energy partition to the workpiece with CBN can be attributed to its very high thermal conductivity (CBN = 3.3 cal/ºC.cm.s and Al_2O_3 = 0.08 cal/ºC.cm.s) whereby a significant portion of the grinding heat is transported to the abrasive instead of to the workpiece. The much lower energy partition to the workpiece with CBN wheels results in much lower grinding temperatures and a greatly reduced tendency for thermal damage to the workpiece. Therefore, the incidence of the film boiling can be reduced, improving the use of water-soluble fluids, due to the lower grinding zone temperatures when using CBN wheels.

The performance of the cutting fluids will be improved if the cutting fluid delivery system is improved too (Webster, 1995). It means that all the delivery system (pump, nozzle design, and pipes) must be managed to obtain high quality workpieces. Round nozzles, based on a fire hoses ones (Rouse *et al.*, 1952) can improve jet coherence (Webster, 1995).

The jet velocity should be increased to match the grinding wheel speed to overcome the air-barrier created by the grinding wheel spindle. According to Webster (1995, 1999) a matched wheel-to-coolant speed ratio is optimum for most applications, except where pump cost or power consumption is excessive.

3. THE INFLUENCE OF THE CUTTING FLUID TYPE IN THE RESIDUAL STRESS

The grinding process leads to residual stresses which can decrease the mechanical resistance of the ground material. The residual stress are induced due to non-uniform plastic deformations close to the workpiece surface. Mechanical interactions between the abrasive grains and the workpiece lead to compressive residual stresses, due to localized plastic displacements, which can be compared to the shot-penning. The tensile residual stresses are caused by thermal induced stress and plastic deformation associated with the grinding temperatures and its thermal gradient (Malkin, 1989). Commonly, most of the residual stresses in grinding are tensile residual ones, indicating that they are thermal induced. Compressive residual stresses can increase the fatigue life and the mechanical proprieties of the ground component. In the other hand, tensile ones are harmful, decreasing the mechanical and corrosion strength and the fatigue life.

The cutting fluid can influence in the residual stress. It needs to guarantee chip formation instead of plowing, keeping the abrasive grain sharp, reducing the friction coefficient between grain and workpiece. Consequently, less heat will be generated during the grinding process (Hitchiner, 1990), decreasing the specific grinding energy (Malkin, 1989). Furthermore, the cutting fluid cooling rate is extremely important when grinding hardened steels due to formation of untempered martensite, resulted from the overheating of the surface followed by rapid quenching, leading to tensile residual stresses in the subsurface .

4. TEST METODOLOGY

The grinding tests of the inlet engine valves were conducted in a CNC cylindrical grinding, SULMECÂNICA, model RUAPH 515-CNC. The material of test specimens was the stainless steel SAE HVN-3, tempered and quenched, 60 HRc, in a cylindrical shape. Its final diameter was 23.8 mm and it was 35 mm long. Before the grinding tests, and after the tempering, the test specimens were turned, in order to correct their dimensional and geometrical errors. This operation was performed using a EMCO turn, model Turn 120, with the following cutting conditions: cutting speed (v_c) = 67 m/min; feed (f) = 50 mm/min. The insert used has the CCMT 09 T3 08 – UR ISO specification and a SCLCL 1212 D09 tool holder. The cutting fluid used was a 5% soluble oil.

Four different types of cutting fluid were tested: a cutting oil, an E.P. mineral oil without chlorine additives and nitride; 8% soluble oil (vegetable emulsion), a biodegradable vegetable soluble oil; 8% soluble oil (mineral emulsion), a mineral emulsion with non-chlorine E.P. additives and 8% synthetic fluid. The cutting conditions applied in the grinding tests were: cutting speed (v_s) = 60 m/s; workpiece diameter (d_w) = 23.8 mm; plunge speed (v_f) = 1.2 mm/min; h_{eq} = 0.025 μm; grinding wheel penetration (a) = 200 μm, grinding width (b) = 15 mm. The spark-out time was 5 seconds.

In order to evaluate the most appropriated type of cutting fluid to be used in the inlet valve grinding, the cutting fluid application system was improved. A new round nozzle based on Rouse *et al.* (1952) one was developed, with exit diameter (D_n) equal to 6 mm. A 5-bar pressure pump was installed, which permitted the maximum v_j equal to 31 m/s, when using the most viscous cutting fluid (cutting oil). Consequently, the ratio v_j / v_s applied in this research was, approximately, equal to 0.5. The tests were performed using a 19A100SVHB grinding wheel, dressed with Ud equal to 8, reproducing in the laboratory the same dressing condition and using the same grinding wheel adopted in the TRW factory, where this grinding operation is originally performed. In order to verify the influence of the grinding wheel wear in the outlet parameters (roughness, and residual stress), for each trial, varying the cutting fluid type, 103 grinding cycles were performed with the cutting conditions mentioned later.

The R_a roughness was measures using a Taylor Hobson mechanical profiler, model Surtronic 3+. The cut-off (lc) used was 0.8 mm and the filter was the 2CR-phase correct according to the NBR 6405/1998. The residual stress were measured using a 4 circles difractometer SIEMENS, model D5000, using chrome as an x-ray radiation. To the determination of the nominal values of residual stress were used the $\sin^2\psi$ two exposure method, according to the Information Report SAE J784a. The maximum X-ray penetration from the surface was equal to 15 μm. The wheel wear profile was measured a TESA displacement gauger, model TT10.

5. RESULTS AND DISCUSSION

5.1 Roughness results

In Fig. 1 were presented the R_a roughness results, varying the fluid type. Four different roughness measurements were performed in the test specimen surface, in 4 different angular positions.

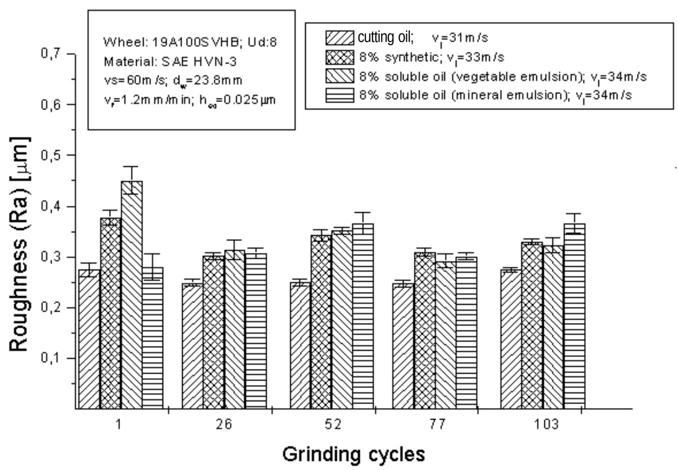

Figure 1 - The average roughness values for each test

In order to analyze the roughness results, the two-way ANOVA was used combined with the Student-Newman-Kleus Method, for all pairwise comparison.

Due to the non-normality of the results, the original data was mathematically transformed, and the ln of the original roughness values was calculated. The ANOVA chart, for the transformed values, is presented in the Table 1.

Table 1 – Analysis of variance – two factors (Two-way ANOVA)

Source of variance	Degrees of freedom	Sum of squares	Mean square	"F"	p
Cutting fluid type (C)	3	0.951	0.31711	168.4	<0.0001
Grinding cycle (G)	4	0.327	0.08177	43.4	<0.0001
CxG	12	0.113	0.04472	23.7	<0.0001
Residual	60	1.928	0.00188		
Total	79		0.24410		

As presented in the Table 1, there is statistical difference among the fluids and among the cycles and among the combined factor (fluid type and grinding cycle) ($p<0.0001$)). Analyzing the roughness results, among the fluids, the cutting oil was the fluid that presented the lowest values for all grinding cycles ($p<0.05$). Besides, the cutting oil presented the most stable roughness behavior, decreasing the roughness value for cycles 1-26, keeping it stable until cycle 77, and then increasing again the roughness to approximately the same cycle-1 value ($p<0.05$). The reason for the best cutting oil results are its highest lubricity, which decreases the coefficient of friction, leads to the chip formation instead of plowing, keeping the grinding wheel sharp, reducing the roughness values.

Among the water-miscible fluids, in the first grinding cycle, the 8% soluble oil (mineral emulsion) presented the best roughness result ($p<0.05$). Otherwise, for the cycles 26 and 52, there's no statistical differences between the synthetic and the vegetable emulsion. In the cycle 26 the mineral emulsion presented the best result and then in the cycle 52 the synthetic and the vegetable emulsion were the best ones ($p<0.05$). For the cycles 77 and 103, the best water-miscible was the vegetal emulsion ($p<0.05$). Although, excluding the first cycles, the maximum difference observed among the water-miscible, for all other cycles was less then 0,02 μm, which is not significant in terms of a practical roughness values. This fact of similar performance for the water-miscible fluids can be attributed to the film boiling effect (Lavine & Malkin, 1990), which neglects the cooling and reduces the lubricant effects of this fluid types in the grinding zone. The cutting oil is less sensitive to the film boiling as reported by Yasui &Tsukuda, (1983).

5.2 Residual stress results

The residual stress values obtained refer to the stresses measured at 15 μm below the surface, due to the x-radiation type used (Chrome) and the atomic plane (110) of the electron iron (alfa phase) analyzed. The residual stress values after tempering and turning were 425 MPa tensile and 450 MPa compression, respectively. Analyzing these results, it was possible to verify that, after turning, all the test specimens presented compression residual stress, due to the machining process used to correct their geometrical and dimensional errors. The state of compression indicates that non-thermal damage was imposed during the turning before the tests. The Fig. 2 presented the residual stress values for each cutting fluid tested.

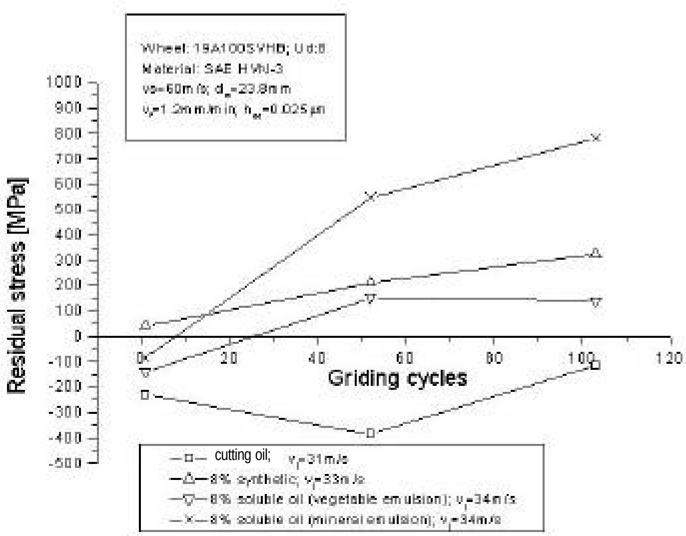

Figure 2 –Residual stress values measured after the grinding tests

In Fig. 2 it is possible to verify that, after the dressing operation, for the first grinding cycle, most of the cutting fluids can generate compressive residual stress, except the synthetic one. It seems that, with the grinding wheel still sharp, less heat is generated and, even with high cooling rates, it is still possible to expect compressive residual stress, as observed by Brinksmeier (1982). Although, the synthetic one presented the highest cooling rate, and even for the first cycle, the re-tempering can occur (Johnson, 1986). For the other cycles, except for the cutting oil, the fluid generated tensile residual stress, due to the high cooling rate, but mainly due to the increase in the heat generated in the grinding process, function of the abrasive grain wear (Johnson, 1986).

The cutting oil was the fluid that lead to the best residual stress results, for all the cycles, even when using a conventional grinding wheel. This fact was also observed by Brinksmeier *et al.* (1982). Due to the film boiling effect, the higher water-miscible cooling ability can be neglected in the grinding zone. Consequently, this cooling advantage over the cutting oil is not responsible for any improvement in the residual stress condition. The reason for the best cutting oil results is its highest lubricity, which decreases the coefficient of friction, leads to the chip formation instead of plowing and keeps the grinding wheel sharp. It allows blunter grits to cut, reduces the overall grinding force levels and generates less heat during the process, as observed by Hitchiner (1990) and Brinksmeier (1982). Consequently, the plastic deformations occurring in the grinding zone lead to compressive residual stresses.

5.3 Wheel wear results

The radial wheel wear values, measured after each test, varying the cutting fluid type were presented in Fig. 3.

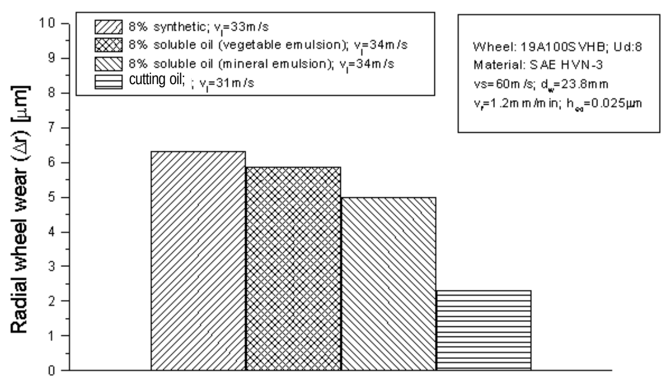

Figure 3 – Radial wheel wear values

It was possible to verify that the wheel wear can be reduced if the cutting oil was used as a cutting fluid, as observed by Carius (1989) cited by Webster (1995), due to its higher lubricity, which can makes the wheel sharper, inhibiting glazing and capping of the grits by the decrease of the coefficient of friction, as observed by Hitchiner (1990). In the Fig. 3 it can be seen that the decrease in the lubricity capacity (mineral emulsion to synthetic) of the cutting fluid leads to the increase in the radial wheel wear.

6. CONCLUSIONS

For the inlet engine valve grinding operation, using an alumina conventional grinding wheel, the cutting oil is the most adequate cutting fluid to be used, due to its tendency in reducing the roughness, the wheel wear, due to its higher lubricity and ability in keeping the wheel sharp for longer periods of time. The main factor of choice was the compressive residual stress generated during all grinding cycles by this type of cutting fluid, which can increase the fatigue life and the mechanical proprieties of the ground component.

Acknowledgments

The authors wish to thank the financial support given to this research by **FAPESP** and by the following companies: **HOUGHTON DO BRASIL**, **MASTER DIAMOND FERRAMENTAS LTDA.**, **TRW DO BRASIL, DE BEERS DO BRASIL** and **SAINT GOBAIN ABRASIVES**.

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