II CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
II NATIONAL CONGRESS OF MECHANICAL ENGINEERING
12 a 16 de Agosto de 2002 - João Pessoa – PB

THERMAL DAMAGE IN INLET ENGINE VALVES DUE TO THE ADOPTED GRINDING WHEEL AND CUTTING FLUID COMBINATION

Eduardo Carlos Bianchi
São Paulo State University - UNESP – Mechanical Engineering Department - Cx. P. 473 - 17033-360 - Bauru, SP, Brazil. e-mail: bianchi@feb.unesp.br

Eraldo Jannone da Silva
University of São Paulo- USP – São Carlos Engineering School – EESC - 13560-250- São Carlos, SP, Brazil. e-mail: eraldojs@sc.usp.br

Paulo Roberto de Aguiar
São Paulo State University - UNESP – Electrical Engineering Department - Cx. P. 473 - 17033-360 - Bauru, SP, Brazil. e-mail: aguiarpr@feb.unesp.br

Abstract. *This paper presents an experimental research in which the thermal damage in inlet engine valves grinding was evaluated. Four different cutting fluids (cutting oil and three different types of soluble oils) and two grinding wheels (alumina and vitrified CBN) were tested. As evaluation parameters, the workpiece residual stress and the micro hardness and the optical observation of the workpiece microstructure were analyzed. The cutting fluid and the grinding wheel types adopted resulted in different types of residual stress due to the different lubricant abilities among the fluids and due to the differences in the mechanical and thermal properties among the abrasives tested. The use of the cutting oil resulted in compressive residual stresses, even using the conventional wheel. The CBN wheel, due to the best proprieties of its grains resulted in compressive residual stresses for all the cutting fluids tested by the reducing of the grinding energy and its easier dissipation from the grinding zone. The microstructure investigations showed that the source of the tensile residual stresses observed was the thermal cycles imposed. No microstructure alterations (presence of UTM and OTM) were detected. Although, the absence of microstructure alterations not always suggests that favorable residual stresses can be obtained.*

Keywords**:** grinding wheel, cutting fluid, residual stress

1. INTRODUCTION

Conventional grinding is a manufacturing process with a relatively high power density input. During grinding, due to the chip formation mechanism, a great part of the produced energy is converted into heat and high temperatures are generated at the interface between the abrasive grain and the workpiece. These temperatures are the main source of damage on the machined surface (Shaw, 1984). Besides the grinding temperature, the cooling rates and temperature gradients are factors, which influence surface integrity predominantly.

It was found that thermal stresses generated in the grinding process were the primary cause of the tensile residual stresses (Chen *et al.*, 2000), which cause a reduction in the service life under stress corrosion or fatigue conditions. In many cases, the thermal damage of the workpiece limits the productivity of advanced grinding methods. Besides the tensile residual stresses, the formation of the untempered (UTM) and overtempered martensite (OTM) and cracks are aspects that are also related with the ground surface integrity (Johnson, 1990).

The reduction of the thermal damages in grinding and the achievement of the surface integrity require the full understand and control of the energy partition, which is the portion of the generated energy in the grinding process that flows as heat into the workpiece. The maximum grinding temperature is determined from the energy conducted into the workpiece, which depends on the heat transfer capacity of the four main elements, which are the wheel, the chips, the fluid and the workpiece. As a result, the thermal damage and the residual stresses in grinding can be controlled by the adoption of the most effective cutting fluid and grinding wheel types, associated with the right selection of the cutting conditions.

This paper presents a comparative study in which the surface integrity of inlet engines valves, ground with different combinations of cutting fluids and grinding wheels was analyzed. The evaluation parameters were the workpiece residual stress, the micro hardness, and the optical observation of the subsurface microstructure. As these valves are submitted to fatigue conditions in service, special attention was given in the residual stress results analyze, identifying the possible sources of the observed residual stresses.

2. THERMAL DAMAGES IN GRINDING

2.1. Surface overheating, cracks and untempered (UTM) and overtempered (OTM) martensite formation

The most common thermal damage in grinding is the surface overheating (burn). In easy to quench materials, the surface overheating followed by the rapid quenching commonly causes the formation of the UTM. If the UTM is present it will generally be found on the top layer of the surface region, which is subjected to the maximum quenching rate. The UTM layer will be harder and more brittle than the base material and is often the source of cracks in the surface. The UTM will show up as a white layer when nital etched.

The formation of OTM also results from overheating of the ground surface. Quenching at a slower rate will case an overtempering of the surface. The OTM will be softer than the base material and show up as a darker layer when nital etched. When UTM is present, a region of OTM will generally be found underneath between the UTM region and the base material. According to Field & Kahles (1985), the presence of even small amounts of OTM and UTM will cause a significant reduction in the fatigue strength of the component. Even with subsequent vacuum retempering, the fatigue strength can’t be significantly improved.

Surface cracks also results from excessive heat during grinding. Their severity will vary. In some situations, the cracks cannot be visible immediately after grinding but will appear at some time later.

2.2. Residual stresses in grinding

Residual stresses are induced into metals and other materials by any process - mechanical, thermal or chemical - that result in permanent, non-uniform change in shape or volume. Low residual stress after grinding is an important requirement for surface integrity of stress sensitive components (Chen *et al.*, 2000). Compressive residual stresses can increase the fatigue life and the mechanical properties of the ground component (Malkin, 1989). If tensile residual stresses remain in the surface, the subsequent service life is reduced under stress corrosion or fatigue conditions.

In general, residual stresses in grinding are primarily generated due to three effects (Chen *et al.*, 2000):

- Thermal expansion and contraction during grinding
- Phase transformations due to high grinding temperatures
- Plastic deformation caused by the abrasive grains of the grinding wheel

The first two effects described above generate the thermally-induced residual stresses in grinding and the last one the mechanically-induced ones. Combinations of the thermal and mechanical effects are possible and the resultant stress is determined by whichever effect is stronger.

Compressive residual stresses are related to mechanical deformation during grinding, due to the normal grinding force (Snoyes *et al.*, 1972). They are formed due to the Hertzian compression and shear forces produced by the action of the grains during grinding (Chen *et al.*, 2000; Malkin, 1989). This action leads to permanent grinding deformation in the workpiece surface, preventing the full recovery of the sub-layer elastic deformation.

The tensile residual stresses are generated in grinding mainly due to the prevailing thermal effects. It was found that thermal expansion and contraction in grinding process was the most significant factor in generation of the tensile stress (Chen *et al.*, 2000). According to Malkin (1989) these stresses and the thermal strains are related to grinding temperatures and their gradient from the workpiece surface to its center. In the grinding zone, during the material removal, the thermal expansion of the more heated workpiece material portion, the one that is close to the surface, is constrained by the coldest material portion, located in the subsurface. This fact generates thermally induced compressive residual stresses close to the workpiece surface, which are severe enough to cause plastic flow in compression. In the subsequent cooling, after the grinding heat source has passed by, plastically deformed material tends to contract more than the material in the subsurface. Although, the requirements of material continuity cause the arising of tensile residual stresses in the material surface. In order to ensure the material mechanical equilibrium, compressive residual stresses should appear in the material subsurface, which are, in magnitude, inferior to those tensile ones.

The thermally induced residual stresses can be also generated by solid phase transformation during the thermal cycle, followed by rehardening as the workpiece cools. The outermost surface layer becomes untempered martensite, while the sub-layer is tempered. The untempered martensite has a great lattice volume than tempered martensite. The surface residual stress is therefore compressive while the residual stress in the sub-layer is tensile. The hypothesis that the residual stresses can be calculated only as function of plastic deformation under thermal stresses at high temperature is valid for high carbon steel. However, the influence of the phase transformation of a martensite matrix to a ferrite one and vice-versa is not negligible. This effect is most important at the surface of easy-to-quench steels (Snoyes *et al.*, 1972). This case corresponds to the severe grinding burn, where high grinding temperatures are reached, which are above the phase-transformation one.

It is possible to induce compressive residual stress in grinding reducing the generated heat amount and the workpiece temperature, keeping it below the transformation temperature (Snoyes *et al.*, 1972). If thermally induced stresses can be maintained below the material yield stress, there will be not a permanent plastic deformation in the workpiece due to the thermal effect. Consequently, the tensile residual stresses can be avoided (Chen *et al.*, 2000). In this case, the mechanically induced stresses may become dominant, resulting in compressive residual stresses. The grinding temperature control is the key for achieving compressive residual stresses. It can be done keeping the maximum grinding temperature below the transitional one for the onset tensile residual stress for a particular material. This control can be achieved through the heat generation reduction in the grinding zone and its high efficient heat dissipation, decreasing the amount of the total energy that flows through the workpiece as heat.

3. THERMAL DAMAGE CONTROL IN GRINDING

As discussed later, the control of the maximum grinding temperature is the key for controlling of the onset tensile residual stresses and the thermal damage. It can be done by the reduction of the generated heat in grinding and its easier dissipation from the grinding zone, reducing the amount of heat that flows through the workpiece. As the maximum energy conducted by the chips is limited and, for steels, equal to 13.8 J/mm^3 (Malkin, 1989) any improvement in the heat transfer in the grinding zone must be done taking account the other elements, the cutting fluid and the grinding wheel. Combined with the right selection of the cutting conditions, the correct use of the most appropriated cutting fluid and grinding wheel types can reduce the thermal damage, avoid the cracks arising and allow the prevalence of the plastic deformation and the compressive residual stresses.

The cutting conditions can influence the thermal damage in grinding. The more severe is the operation (increased material removal rate) the greater is the tendency of thermal damage arising.

The cutting fluids can influence the magnitude of the residual stress and the thermal damage. In the grinding zone, due to the film boiling effect (Yasui & Tsukuda, 1983), convective cooling by the grinding fluid can usually be neglected in regular grinding (Lavine e Malkin, 1990). Consequently, the lubricant ability of the cutting fluid seems to be the governing factor to its performance and to reduce the heat generation. The adequate cutting fluid lubricity guarantees the chip formation instead of plowing, keeping the abrasive grain sharp, reducing the friction coefficient between grain and workpiece and the grinding wheel wear (Carius, 1989). Thus, less heat will be generated during the grinding process (Hitchiner, 1990), decreasing the specific grinding energy (Malkin, 1989) and the thermal damage arising. 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. Otherwise, to be really effective, leading to chip formation instead of plowing, the cutting fluid must be applied in a correct way. Additionally, the use of the most effective cutting fluid type for the required grinding is essential, because among them, some have special features that facilities the chip formation and reduces the overall heat generation.

The grinding wheel type (specification and topography) plays an important role in the heat generation in grinding and its dissipation through the grinding zone. Due to different abrasive grain proprieties (hardness and thermal conductivity), CBN and Al_2O_3 wheels lead to distinct energy partition (Chen *et al.*, 2000), which is the portion of the generated heat in grinding that is conducted as heat to the workpiece, rising its temperature. When comparing to the Al_2O_3 wheels, the use of CBN wheels can lead to a double benefit (Kohli et al., 1995): less heat is generated due to its higher abrasive grains hardness and this heat is easier dissipated through the grains and bond instead of the workpiece, reducing the energy partition. Consequently, more heat is conducted out of the grinding zone lowering the grinding temperatures (Lavine et al., 1989). Thus, the thermal damage is reduced when CBN wheels are used (Malkin, 1985), the burn rarely occurs and the residual stresses are mainly compressive (Tönshoff & Grabner, 1984) (Brinksmeier et al., 1982). The CBN wheel is less sensitive against material removal variations and guarantees compressive residual stresses after long grinding times. The conventional grinding wheel can only generate compressive residual stress when a suitable combination of cutting fluid type and cutting conditions are applied and/or right after dressing. As the amount of material removed increases, the stresses towards tension (Brinksmeier et al., 1982). The dressing parameter is found to be a great impact upon the heat generation in the grinding process. Coarse dressing produces a wheel surface that is open and free cutting. On the other hand, a closed grain structure in the wheel results in wheel surfaces that are not free cutting which leads to an increased thermal impact (Brinksmeier, 1986).

4. TEST METHODOLOGY

The grinding tests of the inlet engine valves were performed in a CNC cylindrical grinding, SULMECÂNICA, model RUAPH 515-CNC. The material of test specimens was the chrome-silicon steel SAE HVN-3 (DIN X 45 CrSi 9 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 an 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 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.

The cutting fluid delivery system was improved. A new round nozzle based on Rouse *et al.* (1952) was developed, with exit diameter (D_n) equal to 6 mm. It is shown in Fig. (1). A 5-bar pressure pump was installed. It permitted the maximum jet velocity (v_j) equal to 34 m/s (approx. flow rate equal to 3,500 l/h) for the less viscous cutting fluid and 31 m/s (approx. flow rate equal to 3,100 l/h), when using the most viscous cutting fluid (cutting oil). Thus, the maximum ratio v_j / v_s, assigned as V^*, applied in this research was, approximately, equal to 0.5. The new round nozzle installed in the grinding machine under operation is also shown in Fig. (1).

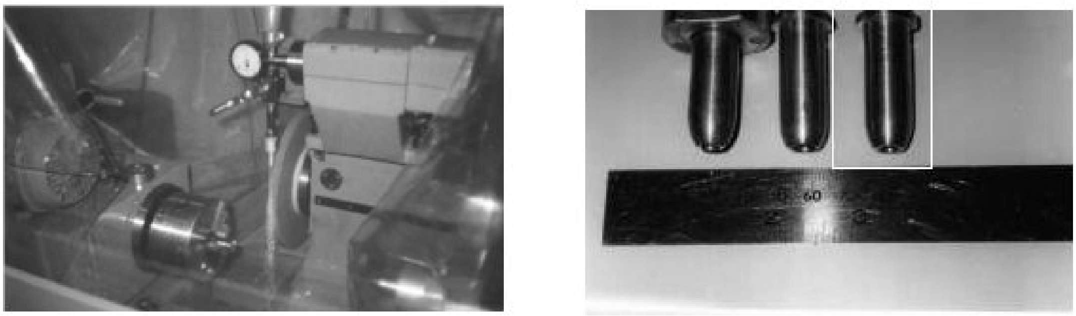
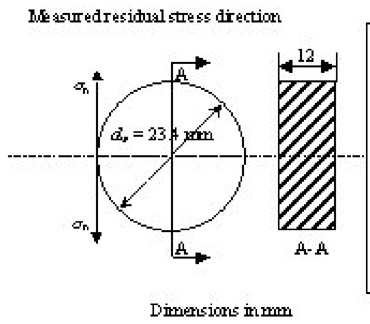


Figure 1. On the right, the round nozzles developed based on Rouse *et al.* (1952) and Webster (1995) (6 mm-D_n nozzle in detail). On the left, the new round nozzle under operation.

The tests were performed using a 19A100SVHB grinding wheel, dressed with dressing overlap (Ud) equal to 8, reproducing in the laboratory the same dressing condition and grinding wheel adopted in the TRW factory, where this grinding is performed on semi finishing and finishing operations. In order to verify the grinding wheel type influence in the outlet parameters, a CBN grinding wheel B76R125V12 was also tested, trued using a diamond rotator disc with speed-ratio equal to 0.7 positive, i.e., the velocity of the rotator disc was 0.7 of the grinding wheel velocity.

In order to verify the influence of the grinding wheel wear in the outlet parameters, for each trial, varying the cutting fluid and grinding wheel types, 103 grinding cycles were performed with the cutting conditions mentioned later.

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 (1971). In this experimental procedure, it is possible to analyze the normal residual stress (σ_n) and the shearing stress (τ) adjusting curves that related the crystallography plane interplanar distances (d) *versus* $\sin^2\psi$, where ψ is the workpiece incline angle. The X-ray residual stress measurements were performed at the Materials Characterization Center (CCDM), located at the São Carlos Federal University (UFSCar), in São Carlos, Brazil. The Fig. (2) presents the direction of the measured residual stress and the operational parameters. The grinding samples were collected after the cycles 1, 52 and 103.



- Maximum X-ray penetration: 15 μm
- X-ray radiation: Chrome;
- Atomic plane analyzed: (110) electron iron (alpha phase);
- Young's modulus and Poison coefficient in agreement with the electron iron, plane (110)
- 2θ scanning angle range was 65 to 72 degrees, steps 0.1 degree;
- Exposure time: 4 seconds;
- Workpiece incline angle (ψ) range: –60 to 60 degrees, steps 10 degrees.

Figure 2. Normal residual stress measuring procedure

For each trial, samples were prepared for the measurement of the micro hardness and for the subsurface microstructure evaluation. The samples include the workpiece material after quenching and turning and all the grinding tests after performing the cycle 103.

The Knoop micro hardness was measured using a Micro hardness Tester Buehler – Micromet 2100 series. The test load was 100 gf. The samples were prepared according to the standard procedures for optical observation of the subsurface microstructure and etched using Vilella (HCl 5 mL, Picric Acid 1g, Ethanol 100 mL).

5. RESULTS AND DISCUSSION

5.1. Residual stress results

The average 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 stresses, due to the machining process used to correct their geometrical and dimensional errors. The state of compression indicates that, before the grinding tests, non-thermal damage was imposed during the turning.

The Figure (3) presents the residual stress values for each cutting fluid and grinding wheel tested. It is possible to verify that, after the dressing operation, for the first grinding cycle, almost all of the cutting fluids can generate compressive residual stress, except the synthetic one, when grinding using the conventional grinding wheel. It seems that, even using the conventional wheel, compressive residual stresses can be generated for the first grinding cycles. With the grinding wheel still sharp, less heat is generated and, even with the poor conductivity properties of the conventional grinding wheel grains it is still possible to expect compressive residual stress. This fact was also observed by Brinksmeier (1986). Although, due to the lower abrasive grain hardness and thermal conductivity when compared with the CBN grains, as the amount removal material increases, the residual stresses measured after grinding using the conventional grinding wheel shift to tension, for all the water-soluble cutting fluids tested. In all the CBN grinding tests, due to the best thermal and mechanical properties of the CBN grains, the generated residual stresses are compressive and presented a stable behavior, guaranteeing compressive values for all the grinding cycles. The lower energy partition obtained when using CBN wheels, combined with the great ability of keeping the wheel sharp lead to a double benefit. Less heat is generated, due to its sharpness maintenance for long periods of time, which favors the cutting instead of the plowing and this heat is more easily dissipated through the wheel instead of the workpiece. There is a decrease in the maximum grinding temperatures and the thermal damage rarely occurs. The mechanical action of the abrasive grains is predominant over the thermal effects, leading to compressive residual stresses.

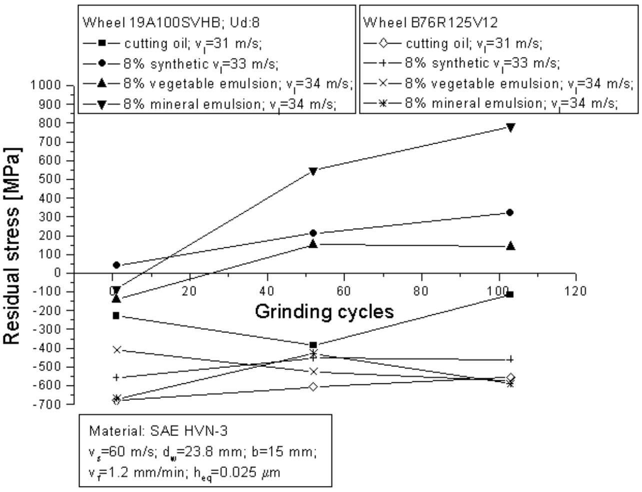


Figure 3. Residual stress values measured after the grinding tests.

As also observed by Brinksmeier *et al.* (1982), the fine dressing operation performed in the conventional grinding wheel (*Ud* = 8) created a closed grain structure in the wheel. Combined with the poor mechanical and thermal abrasive grain properties, these facts resulted in wheel surfaces that are not free cutting, which accelerated and increased the thermal impact.

Regarding only to the grinding wheel type, the CBN one presented the best residual stress results, do not depending of the cutting fluid type.

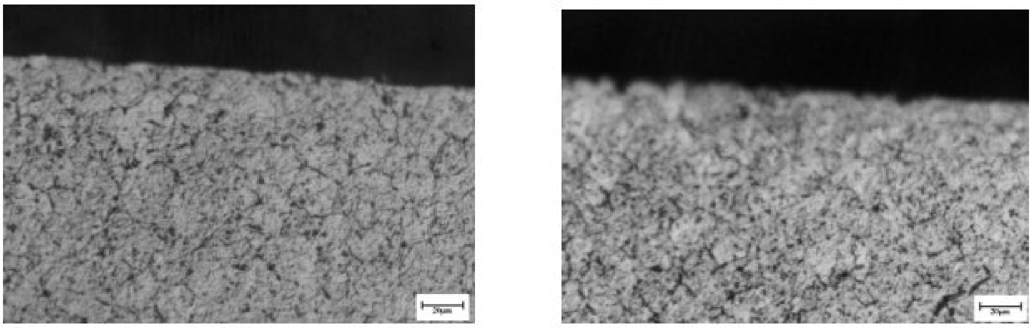
It was possible to verify that the cutting fluid type has a great influence in the residual stress behavior, mainly when conventional grinding wheel is used.

According to the results, even so the cutting oil has a poor convection heat transfer when compared with the water-based ones, it was the only one that could result on the workpiece compressive residual stresses, for all the cycles, when using the conventional grinding wheel. This fact is related with the superior lubricant ability of this cutting fluid. As also observed by Hitchiner (1990), the cutting oil promotes the cutting rather than plowing and sliding, keeping the wheel sharp, due to the friction reduction between the abrasive grain and the workpiece. Consequently, there is a decrease in the specific grinding energy (Malkin, 1989), in the maximum grinding temperatures and in the thermal damages. This feature of residual stress reduction when using cutting oil and conventional grinding wheel was also observed by Brinksmeier *et al.* (1982). Even the water-miscible cutting fluids having a higher heat transfer capability when comparing with the cutting oil, this advantage cannot imply in any improvement in the residual stress, due to the film boiling effect. This effect can more easily occur when using conventional grinding wheels and water-miscible fluids, due to the higher grinding temperatures and the lower boiling point of these fluids (approx. 100 ^{o}C), which can be easily surpassed when using this type of grinding wheel. It seems that the cutting oil with higher lubricant capability can outweigh its poor heat transfer ability through the reduction of friction and the abrasive wear, leading to less heat generation.

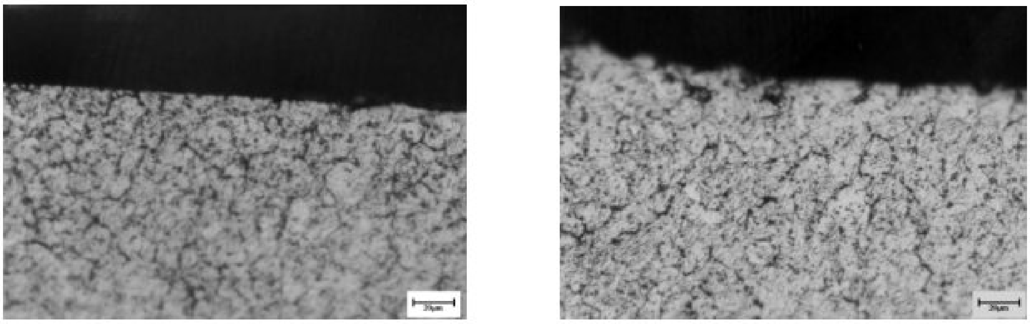
The same behavior of decreasing the residual stresses when using different types of cutting fluids could not be observed in the CBN grinding wheel tests. It seems that due to the superior thermal and mechanical properties of its abrasive grains, the amount material removal performed in each test (103 grinding cycles removing, in volume, 194 mm^3 of material) were not sufficient enough to cause sharpness reduction in the CBN grinding wheel.

5.2. Micro hardness and optical subsurface observation

The Fig. (4) presents the optical observation of the subsurface after the quenching, turning and the grinding tests. The Fig. (5) presents the micro hardness results for all grinding test.



Quenched **Turned**



Conventional wheel, cutting oil, v_j = 31 m/s **CBN wheel, cutting oil, v_j = 34 m/s**

Figure 4 - Optical observation of the subsurface after the quenching, turning and two grinding tests (scale: 1 division = 20 µm)

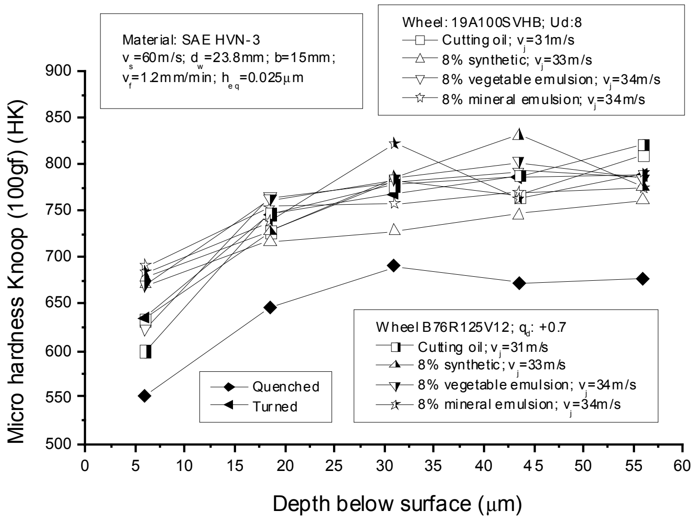


Figure 5 – Micro hardness Knoop results (test load 100 gf)

The combined analyze of the optical observation of the subsurface and the micro hardness results show that microstructure alterations were not observed either by the subsequent operations (quenching, turning and grinding) or by the application of different cutting fluid and grinding wheel combinations. The structure was always martensite with no presence of OTM or UTM. The micro hardness characteristics after the turning was preserved, with no significant alterations due to the cutting fluid and grinding wheel combination. Although, even with no microstructure alterations, in the tests, the different residual stress types observed when using different cutting fluid and grinding wheel combinations can be attributed to the prevailing of the mechanical or thermal actions. For this grinding tests, the tensile residual stress results observed in Fig. (3) can be attributed to the thermal cycle imposed, heat and subsequent cooling, with different rates in different material portions, as suggested by Chen *et al.* (2000), Malkin (1989) and Snoyes *et al.* (1972). As suggested by Chen *et al.*, (2000), thermal expansion and contraction in grinding process was the most significant factor in generation of the tensile stress. The use of conventional wheels with a non-effective cutting fluid (poor lubricity) can lead to higher grinding temperatures. These temperatures, followed by an inappropriate cooling rate impose a thermal cycle, which allows the generation of thermal stresses, canceling the mechanical action of the grains during cutting, which could lead to compressive residual stresses.

6. CONCLUSIONS

According to the results obtained in this research, the authors conclude that:

The magnitude and the type (tension or compression) of the residual stress due to grinding can be influenced by the cutting fluid and the grinding wheel types.

The use of CBN grinding wheels can significantly reduce the thermal damage in grinding, and, consequently, permit the generation of compressive residual stresses on the ground material surface. These stresses, instead of thermally induced ones, arise due to the prevailing of the plastic deformations caused by the abrasive grain. The conventional grinding wheels can also generate compressive residual stresses, although with less intensity and only for the first grinding cycles or when a suitable cutting fluid is applied (cutting oil). With the increase of the removed material, the residual stress tendency is shift to tension. On the other hand, the compressive residual stresses generated when grinding with CBN wheels are greater in intensity and much less dependent of the removed material.

The cutting fluid type can sensibly influence the grinding residual stresses and the radial wheel wear. When grinding with conventional wheels, the use of cutting oils can allow the generation of compressive residual stresses in the workpiece, even using a grinding wheel that its grains have inferior mechanical and thermal properties than the CBN ones. When comparing to the other cutting fluids, the superior lubricant ability of the cutting oil reduces the coefficient of friction between grain and workpiece and promotes the cutting instead of plowing. It keeps the wheel sharp, reduces the generated heat in grinding and decreases the thermal damages.

Due to the film boiling, the cooling properties of the water-miscible fluids can be neglected and don’t cause any improvement in the reduction of the grinding residual stresses. The absence or poor mineral oil content of some water-miscible fluids lead to any significant reduction in the abrasive workpiece coefficient of friction, neither in the spent grinding energy. The increase in the mineral oil content can significantly reduce the radial wheel wear, mainly when grinding with CBN wheels. Chemical reactions in the CBN grains when using water-miscible fluids can lead to a premature abrasive wear.

The investigations about the microstructure before and after grinding showed that the source of the tensile residual stresses observed was the thermal cycles imposed (microstructure changes). No microstructure alterations (presence of UTM and OTM) were detected. Although, the absence of microstructure alterations not always suggests that favorable residual stresses can be obtained.

7. ACKNOWLEDGMENTS

This research was supported by **FAPESP** and was performed in **FE - UNESP Bauru – São Paulo,** in collaboration with the **NUMA (OPF Group),** located in the **EESC – USP São Carlos – São Paulo**, and with the following companies: **HOUGHTON DO BRASIL**, **MASTER DIAMOND FERRAMENTAS LTDA.**, **TRW DO BRASIL, DE BEERS DO BRASIL** and **SAINT-GOBAIN ABRASIVES**.

8. REFERENCES

Brinksmeier, E., 1986, “A Model for the Development of Residual Stresses in Grinding”, In: NIKU-LARI, A. Advances in Surface Treatments. 5.ed. Pergamon Press, vol. 5, pp.173 a 189.

Brinksmeier, E.; Cammett, J. T.; König, W.; Leskovar, P.; Peters, J.; Tönshoff, H. K., 1982, “Residual Stresses – Measurement and Causes in Machining Processes”, Annals of the CIRP, v. 31/2, pp. 491-510.

Carius, A., 1989, “Effects of Fluid Type and Delivery on CBN Wheel Performance” Modern Grinding Technology Conf. SME, Novi MI 10-12 Oct.

Chen, X.; Rowe, W. B.; McCormack, D. F., 2000, “Predicting the Transitional Boundary of Tensile Residual Stress in Grinding”, Abrasives Magazine, Feb. /Mar. pp. 28-35.

Fields, M.; Kahles, J. F., 1985, “The influence of Untempered and Overtempered Martensite Produced during Grinding on the Surface Integrity of AISI 4340, HRC Steel.” Milton C. Shaw Grinding Symposium, ASME, Miami Beach, Florida.

Hitchiner, M. P., 1990, “Precision Grinding Systems for Production Grinding with Vitrified CNB” SME Technical Paper MR90-507, pp. 1-11.

Johnson, G. A., 1990, “Beneficial Compressive Residual Stress Resulting From CBN Grinding” SME Second International Grinding Conference, p. 12.

Kohli S.P., Guo, C.; Malkin, S., 1995, “Energy Partition for Grinding with Aluminum Oxide and CBN Abrasive Wheels". ASME Journal of Engineering for industry, v. 117, pp. 160-168.

Lavine, A. S.; Malkin, S., 1990, “The Role of Cooling in Creep-Feed Grinding”, International Journal of Advanced Manufacturing Technology, v. 110, pp. 1.

Lavine, A.S., Malkin, S.; Jen, T.C, 1989, "Thermal Aspects of Grinding with CBN Abrasives”, Annals of the CIRP, v. 38/1, pp.557-560.

Malkin, S., 1985, “Current Trends in CBN Grinding Technology”, Annals of the CIRP., v. 34/1, pp. 557-560.

Malkin, S., 1989, “Grinding Mechanisms” e “Grinding Temperatures and Thermal Damage”, In: Malkin, S. Grinding Technology: theory and applications of machining with abrasives. 1.ed. Chichester, Ellis Horwood Limited, Cap. 5 e 6, pp.108 a 171.

Rouse, H., Asce, M., Howe, J.W; Metzler, D.E., 1952, “Experimental Investigation of Fire Monitors and Nozzles, 117th ASCE Transactions.

SAE J784a, 1971, “Residual Stress Measurement by X-ray Diffraction” Society of Automotive Engineers, Inc., Second Edition, pp. 1-119.

Shaw, M. C., 1984, “Grinding Temperatures”, Proceedings of the 12th North American Research Conference, Society of Manufacturing Engineers, Dearborn, MI, USA, pp. 304.

Snoyes, R.; Maris, M.; Peters, J., 1972, “Thermally Induced Damage in Grinding”, Annals of the CIRP, v. 27/2, pp. 571-581.

Tönshoff, H. K.; Grabner, T., 1984, "Cylindrical and Profile Grinding with Boron Nitride Wheels” Proceedings of the 5th International Conference on Production Engineering, Tokyo, pp. 326-343.

Webster, J., 1995, “Selection of Coolant Type and Application Technique in Grinding”. Supergrind, pp. 205-218.

Yasui, H.; Tsukuda, S., 1983, “Influence of Fluid Type on Wet Grinding Temperature”, Bull. Japan Soc. of Precision Engineering., n.2, v. 17, pp. 133-134.