Evaluation of the thermal damages in inlet engine valves varying the grinding wheels and the cutting fluids

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Resumo

Nesse artigo é apresentada uma pesquisa experimental sobre os danos térmicos que aparecem nas válvulas de admissão dos motores após passarem pelo processo de retificação. Foram utilizados, nessa experimentação, quatro tipos de fluidos de corte e dois rebolos (CBN e Al_2O_3), sendo analisadas a tensão residual, a microdureza e a microestrutrura das peças fabricadas com esses materiais. Esses fluidos e rebolos resultaram em diferentes tipos de tensões residuais. O óleo de corte, por exemplo, induziu nas peças tensões residuais de compressão. Em relação ao rebolo de CBN, devido às melhores propriedades de seus grãos abrasivos, estes proporcionaram tensões de compressão para todos os fluidos testados. Em relação às alterações microestruturais, notou-se que nenhuma alteração térmica foi detectada nas peças, embora a inexistência de alterações microestruturais nem sempre sugerem que tensões residuais favoráveis foram obtidas.

Palavras-chave: Retificação, fluidos de corte, rebolos, tensões residuais, danos térmicos, válvulas.

Abstract

This paper presents an experimental research in which the thermal damage in inlet engine valves grinding was evaluated. Four different cutting fluids and two grinding wheel were tested and were analyzed the workpiece residual stress, the micro hardness and the optical observation of the workpiece microstructure. The cutting fluid and the grinding wheel types adopted resulted in different types of residual stress. 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 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 were detected. Although, the absence of microstructure alterations not always suggests that favorable residual stresses can be obtained.

Keywords: *Grinding, cutting fluids, grinding wheel, residual stresses, thermal damage, valves.*

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 that influence surface integrity. 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 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.

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). 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 and plastic deformation caused by the abrasive grains of the grinding wheel. 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 grains during grinding (Chen *et al.*, 2000; Malkin, 1989).

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. 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.

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).

Combined with the right selection of the cutting conditions, the correct use of the most appropriated 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 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 & 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.

When comparing to the Al_2O_3 wheels, the use of CBN 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 are used (Malkin, 1985), the burn rarely occurs and the residual stresses are mainly compressive (Tönshoff & Grabner, 1984).

3. 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, 60HRc, in a cylindrical shape. Its final diameter was 23.8mm and it was 35mm 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)=67m/min; feed (*f*)=50mm/min. The insert used has the CCMT 09 T3 08 - UR ISO specification and a SCLCL 1212 D09 tool holder. The fluid used was 5% soluble oil.

Four different types of cutting 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)=60m/s; workpiece diameter (d_w)=23.8mm; spark-out time of 5 seconds; plunge speed (v_f)=1.2mm/min; h_{eq}=0.025mm; grinding wheel penetration (*a*)=200μm, grinding width (*b*)=15mm. The fluid delivery system was improved. A new round nozzle based on Rouse *et al.* (1952) was developed, with exit diameter (D_n) equal to 6mm. A 5-bar pressure pump was installed. It permitted the maximum jet velocity (v_j) equal to 34m/s (approx. flow rate equal to 3,500 l/h) for the less viscous cutting fluid and 31m/s (approx. flow rate equal to 3,100 l/h), when using the most viscous (cutting oil). Thus, the maximum ratio v_j/v_s, assigned as V^*, applied in this research was, approximately, equal to 0.5.

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 Figure 1 presents the direction of the measured residual stress and some parameters. The samples were collected after 1, 52, 103 cycles.

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

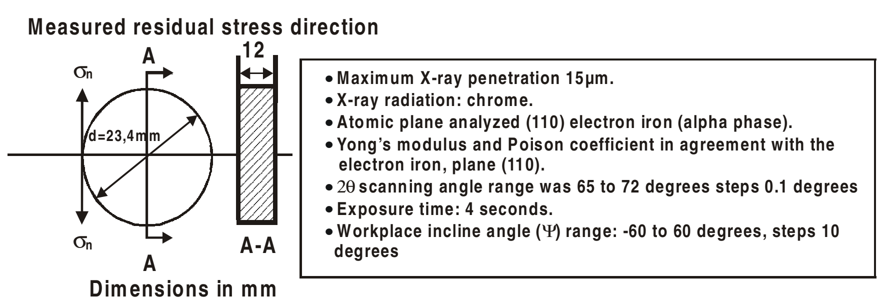

Figure 1 - Normal residual stress measuring procedure.

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).

4. Results and discussion

4.1 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 2 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.

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, in the maximum grinding temperatures and in the thermal damages (Malkin, 1989).

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

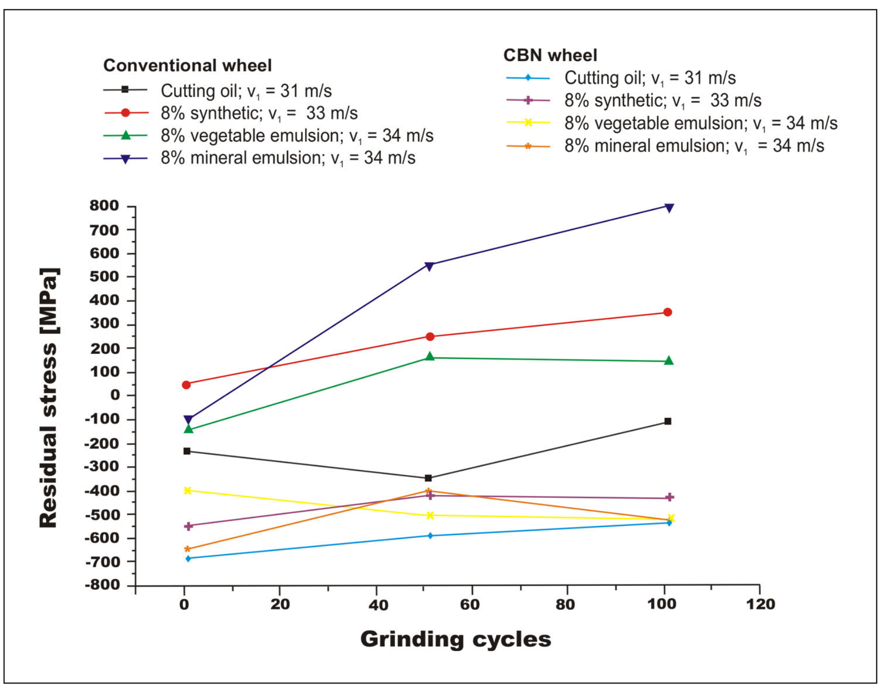

Figure 2 - Residual stress values measured after the grinding tests.

grinding wheels and water-miscible fluids, due to the higher grinding temperatures and the lower boiling point of these fluids (approx. 100ºC), 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 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 (194 mm^3) were not sufficient enough to cause sharpness reduction in the CBN grinding wheel.

4.2 Micro hardness and optical subsurface observation

The Figure 3 presents the optical observation of the subsurface after the quenching, turning and the grinding tests. The Figure 4 presents the micro hardness results.

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 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 Figure 2 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.

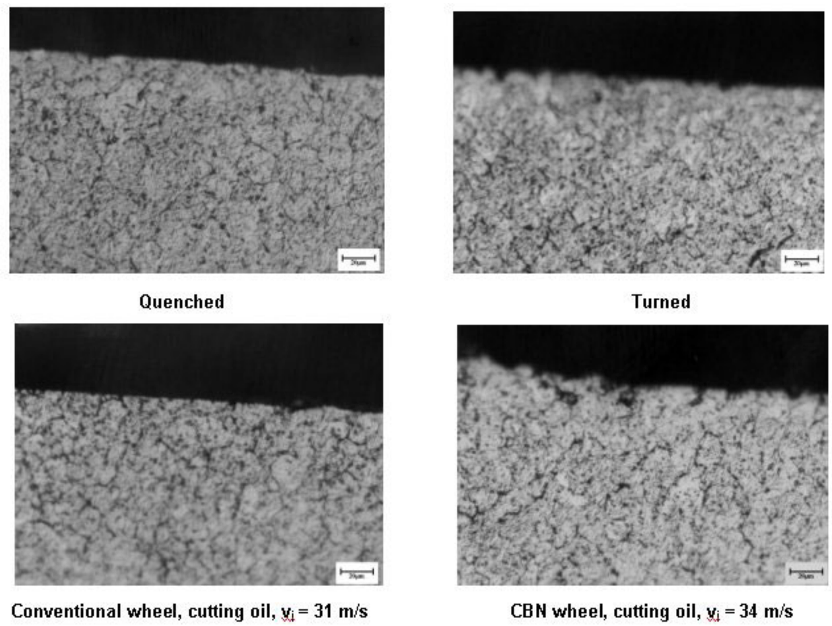

Figure 3 - Optical observation of the subsurface after the quenching, turning and two grinding tests (scale: 1 division = 20 μm). (v_j) = speed of cutting fluid.

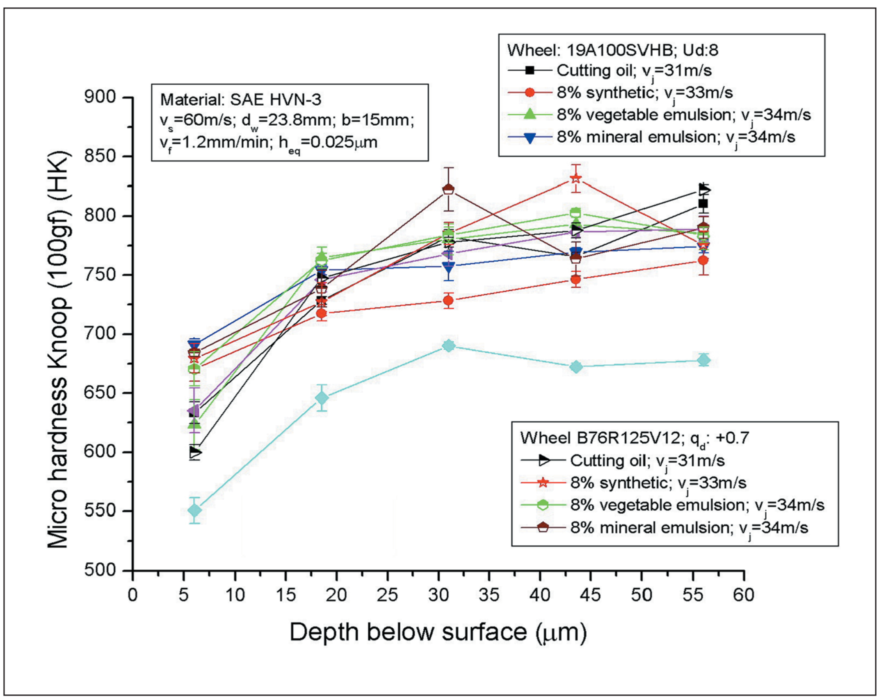

Figure 4 - Micro hardness Knoop results (test load 100 gf). The cutting conditions applied in the grinding tests were: cutting speed (v_s)=60m/s; plunge speed (v_f)=1.2mm/min; h_{eq}=0.025mm; grinding wheel penetration (*a*)=200μm; grinding width (*b*)=15mm; (v_j) = speeds of cutting fluids.

5. 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 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 fluid is applied. 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 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 promotes the cutting instead of plowing.

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 investigations about the microstructure before and after grinding showed that the source of the tensile residual stresses observed was the thermal cycles imposed. No microstructure alterations were detected.

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