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The Use of Cylindrical Grinding to Produce a Martensitic Structure on the Surface of 4340 Steel

Grinding is one of the most widely used manufacturing processes and, in the last few decades, has developed considerably. An example of these developments is hardening by grinding, an operation that is being studied to provide an option to the conventional hardening processes. This study presents the use of a cylindrical grinding process to produce a martensitic structure on the surface of SAE 4340 steel workpieces, and aims at adjusting the parameters of this process. To do much, a set of experiments were carried out using three cycles of grinding: the first one just to obtain a workpiece with regular diameter; the second cycle is that which will provide heating and cooling of the ground workpiece; and the last cycle is to provide corrections to the dimensions and roughness. Results of the experiments showed that hardening by grinding is possible and that the workpiece achieved hardness levels compatible to those provided by the conventional hardening processes. The use of such a process for surface hardening purposes has been researched and developed with a view to increasing the productivity of the process, ensuring dimensional and surface quality, in addition to mechanical resistance.

Keywords: *grinding hardening, material structure, surface hardness*

Introduction

Grinding is one of the most widely used manufacturing processes to achieve appropriate surface and dimensional finishing conditions. Over the last few decades, grinding has developed considerably as new materials were employed to manufacture grinding wheels and new, more rigid machine-tools with greater cutting speeds were designed. The applications of grinding operations have also improved significantly, including roughing operations with great material removal rates.

A good example of such development is hardening by grinding, which was successfully performed by Brockhoff (1999) and Brinksmeier et al. (2003), and which was also studied and performed by Gâmbaro (2006) and by Nguyen et al. (2007). More recently, Han et al. (2007) carried out experimental studies on grinding hardening of non-quenched and tempered steel.

Brinksmeier and Brockhoff (1996) highlighted that the existing heat treatment and grinding experience have two major limitations:

1. There are many heat treatment processes for surface hardening, but they are difficult to integrate into a production line;
2. Subsequent to heat treatment, structural parts are subjected to grinding, in the course of which impairment of hardened materials can arise caused by thermo-mechanical influences of the grinding process (Brinksmeier and Brockhoff, 1996).

These problems led to the use of grinding to harden the surface of structural parts in a carefully directed fashion. This hardening operation can be used to optimize the manufacturing processes of workpieces that need hardening on specific sites only (such as bearings seats or gears, and crankshafts), where greater resistance to friction and wear is required. Hardening improves the performance of workpieces used in tribological functions, in addition to enabling them to stand greater loads.

This article aims to present the optimization of manufacturing processes by replacing traditional hardening operations with grind hardening in cycles. In order to illustrate this process, some test results are shown.

Nomenclature

Ud = *overlap, mm*
Vs = *cutting speed, m/s*
Vw = *workpiece speed, m/min*
F = *plunge speed, mm/rot*

Traditional hardening operations

According to Klocke *et al* (2005), workpieces have some functionality to fulfill after the machining processes:

- mechanical functions (capability of carrying mechanical loads);
- thermal functions (heat resistance or temperature conductivity);
- tribological functions (surface interaction with other media);
- optical functions (visible appearance, light reflection behavior);
- flow functions (influence on the flow of fluids).

The tribological and the mechanical properties of steel can be altered by means of heating and cooling cycles (thermal treatment). As an example, SAE 4340 steel can reach hardness greater than 50 HRc (25 HRc to 30 HRc is the hardness of SAE 4303 non treated), depending on the thermal treatment used. The type of thermal treatment is chosen according to the application, and factors such as heating time and temperature, and cooling speed must also be considered (Callister, 2010).

Brinksmeier and Brockhoff (1996) present a list of methods that the industry can use to harden the surface layer of workpieces. These methods are mechanical, thermal, thermomechanical and thermochemical. A non-traditional method was described by Brinksmeier et al. (2008): the cold surface hardening, where the

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Paper accepted August, 2010. Technical Editor: Anselmo Eduardo Diniz

hardened surfaces are induced by mechanical deformations in processes like deep rolling.

Hardening also comprises heating and cooling cycles that change the structure of materials, in addition to their mechanical properties. Such treatment must be carried out with heating time control to ensure that the temperatures that lead to the transformation of the structure of materials are reached (Callister, 2010).

Close to 500°C the austenitic structure changes to pearlitic. When the temperature reaches 200°C, martensite is formed. It should be pointed out that the formation of martensite (retained) does not arise from the time of transformation, but rather from the heating temperature and cooling rate, as shown on CCT curve for 4340 steel (Fig. 1) (ASM Handbook, 1991).

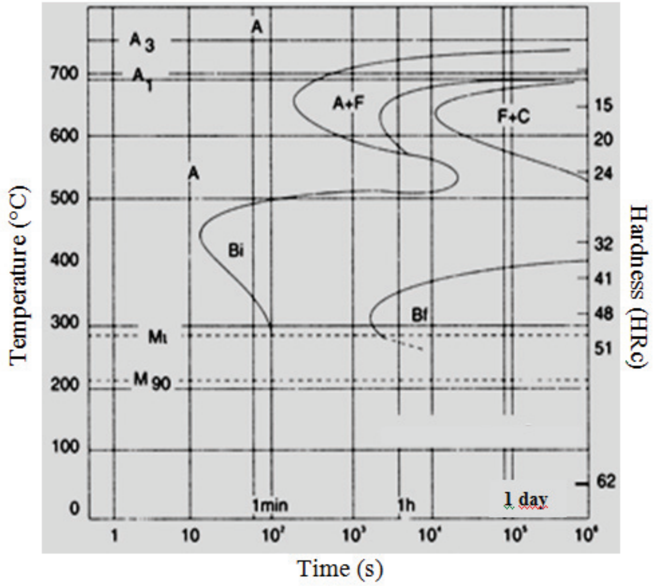

Figure 1. CCT Curves for steel 4340 (ASM Handbook, 1991).

Grinding hardening

Klocke et al. (2005) affirmed that manufacturing processes, including grinding, influences the workpiece properties on different levels: macro (influence on accuracy shape and dimensions); micro (surface topography); meso (material structure and properties); and nano (tribochemical reactions layers).

The main characteristic that grinding process presents in comparison to other machining processes is the contact area between tool and workpiece, relatively larger in grinding. This contact and the friction between abrasive grits and workpiece on the chip formation lead to high temperatures on the contact zone, resulting in risks of thermal damages to the workpiece surface layer (Brinksmeier et al., 1999; Hou and Komanduri, 2003). Damages over the workpiece that can occur during the grinding process are very expensive "since all the previous processes before the grinding itself are wasted when a part is scrapped at this stage… Hence, the damage control in grinding process is of great interest to every industry dependent on this process" (Aguiar et al., 2006).

Malkin and Guo (2007) affirmed that thermal damage is one of the main limitations of the grinding process, and that it is important to understand the factors which affect grinding temperatures. Most of grinding damages have a thermal origin. The temperatures generated during grinding are a consequence of the energy expended by the process and, in general, the energy or power consumption is an uncontrolled output of the grinding process. Outwater and Shaw (*apud* Hou and Komanduri, 2003) reported that 35% of the thermal energy generated during cutting contact flows into the workpiece.

According to Abrão (1991), the temperature gradients in the contact region between wheel and workpiece can reach 1000°C and above, which is enough to cause damage to the surface integrity of ground materials. One such damage is the so-called "grinding burn", a kind of surface integrity damage that occurs when ground surfaces oxidize and decarburize (Abrão, 1996).

Malkin (1989), *apud* Dotto et al. (2006), affirmed that a bluish coloration on the surface of the part characterizes the visible burning in steels: "This coloration generally is removed by the 'sparkout' period at the end of the grinding cycle, but this effect is cosmetic, and the absence of coloration on the ground surface does not mean necessarily that the burning of the part did not occur".

Aguiar et al. (2005) classified grinding burn in four categories: non-burn, slight burn, medium burn and severe burn, and established that it can be detected visually, according to the set of patterns shown on Fig. 2.

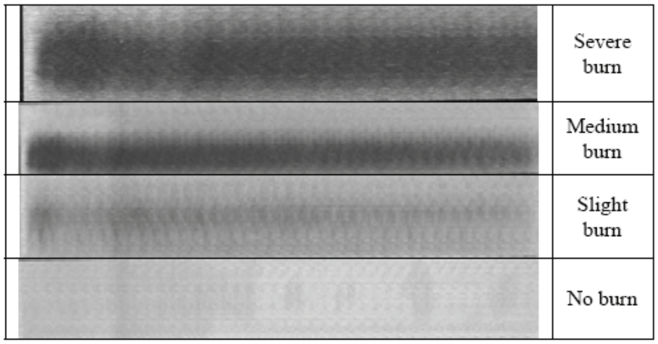

Figure 2. Patterns of grinding burn for visual detection (Aguiar et al., 2005).

However, Shaw (1994), Lima (2008) and Webster (2007) found out that the damage is a result of uncontrolled or poorly executed grinding operations, and it happens only if removal rates used are inadequate or if wheel wear is excessive.

An increase in temperature in the contact region between wheel and workpiece is not enough, in itself, to change the structure of materials and to lead to phase transformation. The contact between wheel and workpiece is not long enough for the changed structure to stabilize. However, the elastic and plastic deformation that occurs during chip formation in the grinding process accelerates the transformation of the structure of the material during heating because there was the contact between grain and material through the diffusion of martensite on the pearlitic structure (Shaw, 1994).

As a result, the changes in material structure that occur during the grinding processes (as shown by Lima (2002) and Lima (2008)) are of beneficial consequence that can be used to help hardening the ground surface layer in a controlled cycle. It should be pointed out that these changes had always been considered undesirable or even problematic. That is still true for uncontrolled grinding cycles.

Grind hardening needs to be severe for higher temperatures to be reached on the contact region between wheel and workpiece, in order to heating the inner of the workpiece in a layer compatible to the hardened thickness desired. Therefore, grinding roughing operations must be sufficiently aggressive for the surface to heat appropriately. However, if the heating is excessive as a result of over-aggressive grinding, unwanted damage, rather than the desired structural changes, may arise.

In their experiments, Brinksmeier et al. (2003) found that the heating speed can reach thousands of degrees Celsius per second. For this reason, grinding conditions must be controlled; otherwise, results may totally differ from the outcome.

Grind hardening is an option for the applicable industrial operations. The tests performed by Brinksmeier et al. (2003), with considerable rates of repetitiveness and reproducibility, showed significant results also in terms of dimensions and form tolerances. These tests were performed without coolant or dressing during the grinding cycle. Consequently, the process offers a great potential for optimizing further research.

Han et al. (2007) also showed the potential of grinding hardening on experiments with non-quenched and tempered steel reaching hardened layers greater than 1.0 mm. However, as the tests were done under very severe conditions and without control of dressing, they cannot be considered as a reference for the experimental part of this research.

Purpose of a grinding hardening cycle.

In order to obtain the desired hardened surfaces by means of grinding, it is necessary to complete a three-phase grinding cycle, as follows:

- the first phase consists of a regular grinding operation, just to remove previous imperfections from the other machining operations;
- the second phase is the hardening cycle, which entails a very aggressive roughing grinding operation to assure that heating of workpiece, as described previously, occurs. This phase can be done with or without coolant, and preferably in a single turn of the workpiece. As it is an aggressive roughing operation, the roughness achieved is not compatible to those achieved in grinding operations;
- the third phase is the finishing grinding cycle, with a view to obtaining the desired surface quality (roughness) and relieving the stress on the ground surface. If grinding burn occurs during phase 2, it is removed during this phase. The grinding conditions in this phase are those generally used for finishing operations. The occurrence of phase 3 eliminates the need for spark-out on phase 2.

In such a grinding cycle, it is necessary to leave enough material along the diameter of the workpiece so that both the hardening and the finishing operation can be performed, and surface quality is achieved, as shown in Fig. 3 (Brinksmeier et al., 2003).

For grinding hardening to occur, the contact forces between workpiece and wheel, in addition to the time of contact between them, must be exactly those needed for one turn of the workpiece. A single turn should be sufficient for the energy present in the cutting process to undergo thermal and mechanical transformations.

However, after these transformations, residual stresses appear as a result (Brockhoff, 1999), and it is necessary another grinding cycle, under finishing conditions, to relief these stresses. Only after performing this cycle, the grinding wheel must be retreated.

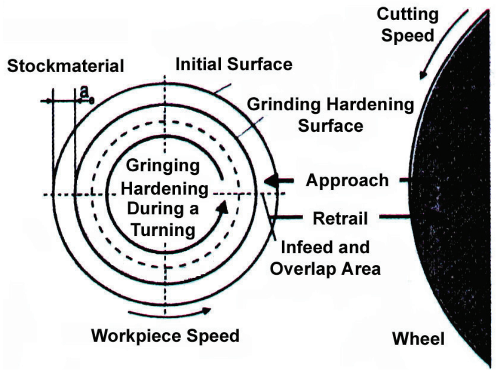

Figure 3. Hardening Grinding Cycle (Brinksmeier et al., 2003).

Materials and methods

A series of tests were carried out in order to provide scientific evidence for the cycle proposed above.

First, a workpiece had to be selected for grinding. As the goal of the experiment was to test the results of a cylindrical plunge grinding operation, a workpiece with two or more seats, as shown in Fig. 4, was chosen.

Subsequently, the material for producing the test specimens was chosen considering the aim of the tests, namely the production of a grind-hardened workpiece through a process that had wide application to industrial environments. SAE4340 steel (supplied with 25 HRc to 30 HRc) was selected for its hardenability and wide industrial use, where surface hardening is required (such as for the production of the seats of bearings or gears).

The parameters and conditions of the grinding operation were defined with a view to controlling infeed plunge speed, cutting depth and workpiece speed, as well as the length of time of contact before the wheel was retreated. These parameters are essential for the reproducibility of the hardened layer. Phases 1 and 3 were normal grinding operations, and the usual pre-finishing and finishing conditions were adopted. For phase 2, more severe conditions were adopted in order to induce heating throughout the cutting cycle.

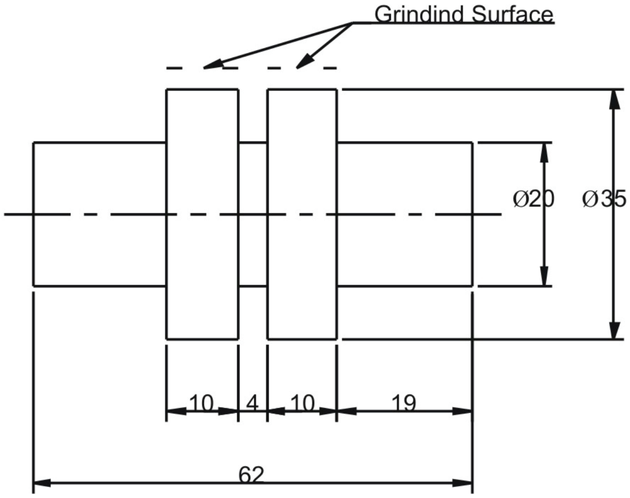

Figure 4. Workpiece used for testing a grinding hardening cycle (Dimensions in mm).

Dressing conditions are also important because they are to determine if the grinding wheel is conditioned for the roughing operations (lower Ud) – inducing more heating of the workpiece during the contact because of the cutting efforts – or for finishing operations (higher Ud).

So, the complete set of conditions was defined as follows:

- dressing with an overlap (Ud) of 5.0 for the pre-finishing and finishing operations, once this is a value more compatible to these operations; and with an overlap of 1.0 for the second phase, once this value is more compatible to operations with a greater removal rate of material;
- a cutting speed (Vs) of 35 m/s for the whole cycle, because it is a usual value in industrial settings;
- workpiece speed (Vw) based on the relationship Vw = Vs/60, widely used in industrial applications, for phases 1 and 3. For phase 2, the value of Vw = 12 m/min was adopted in order to induce hardening in a single turn of the workpiece, which was the purpose of the tests. The result was Vw = 12 m/min;

- appropriate wheel infeed plunge speed (f) for each phase. In phases 1 and 3, in which form, dimensional and surface finishing quality is required, the values adopted for f were the size of micrometers per rotation (actually, 0.005 mm/rot). For phase 2, the infeed speed was in the order of hundredths of a millimeter per rotation (0.05 mm/rot);
- the cutting depth was also based on the cycle objectives. In phase 1, a small amount of material (up to 0.01 mm) was ground in order to achieve the initial form quality of the workpiece. In phase 2, the goal was to have greater interaction between wheel and workpiece and to induce heating of the material. Consequently, up to 0.05 mm of material was removed. And in the third phase, an even smaller amount of material (0.005 mm) was removed, for the final dimension and surface finishing conditions to be achieved;
- the grinding wheel should enable both roughing and finishing operations. A conventional AA80K6V 335 mm x 50.8 mm x 127 mm grinding wheel was used. The wheel surfaces could be changed according to the type of grinding operation. With this kind of wheel, the desired conditions are produced and the wheel profile is maintained throughout the grinding operation;
- coolant (soluble oil, semi-synthetic) was abundantly used in phase 1, and directed to the contact region between wheel and workpiece. Phase 2 was performed without coolant in the contact region (to induce heating). And phase 3 was performed both with and without an abundant supply of coolant. Pressure of the coolant were not controlled during the tests;
- tests were carried out in a C71CN Ferdimat CNC cylindrical grinding machine;
- after the grinding cycle was completed, the surface hardness, micro hardness, and surface roughness of each workpiece were analyzed. Hardness was measured on Rockwell C, with a load of 150 kgf, in a hardness tester: HECHERT (Maximum strength = 250 kgf). Micro hardness was measured with a Microtest MV micro hardness tester (model HL) using loads of 1.0 kgf, according to ASTM E384-99 procedures. Surface roughness was measured with a Mitutoyo Surftest 211 portable surface roughness tester. The images were made with Microscope NIKON: 50x, 100x, 200x, 400x and 100x (Scale graduated ocular). All the measurements above were repeated three times, and a median value was obtained in each case.

Experiment results and discussion

Every workpiece that underwent testing was measured as previously explained and surface hardness, micro hardness and surface roughness results are shown below. Importantly, no signs of burning surface was detected in the tests because, even occurring in phase 2, should have been removed during phase 3.

Surface hardness

Surface hardness values after grinding met the goal of the tests. There was a small difference between phase 3 tests performed with coolant, whose hardness values averaged 53.43 HRc, and phase 3 tests without coolant, whose average hardness value was 47.67 HRc (Table 1). The reason for this difference is that the transformation of the structure of the material was slower in the tests without coolant, as the workpiece was cooled by air alone, than in the tests with coolant. In the latter tests, cooling was faster and occurred immediately after heating, induced by the cutting conditions in phase 2. But in both cases the surface of the workpiece hardened after the grinding cycle, and the hardness values obtained were consistent with those obtained in conventional electrical induced hardening operations, according to the Fig. 5 that shows hardness values around 50 HRc to the SAE 4340 steel (Callister, 2010).

Table 1. Average and standard deviation of HRC Hardness.

Cooling	# Obs	average	Standard deviation
with	7	53.43	0.79
without	7	47.67	0.82

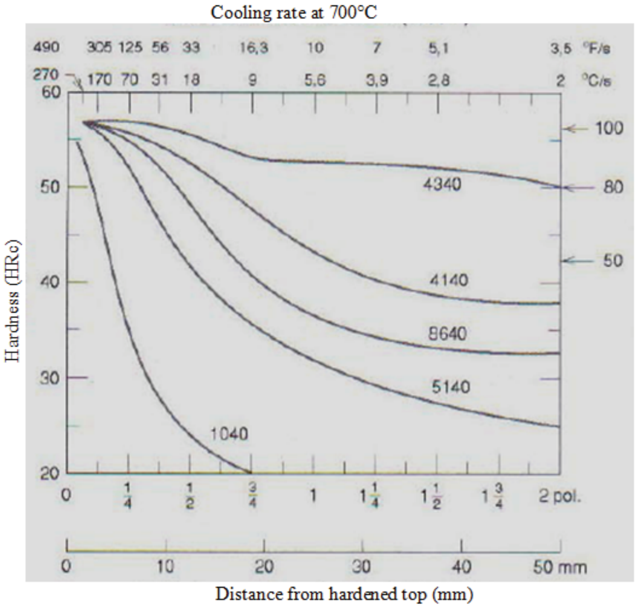

Figure 5. Hardenability of steels 1040, 4140, 4340, 5140 and 8640 (Callister, 2010).

Microhardness

The measurements of microhardness were carried out according to the ASME E384-99 procedures, which define the positioning and distance between measurement impressions. Figure 6 shows that this standard was followed, and the impressions were positioned in a straight line, from the border to the center of the workpiece.

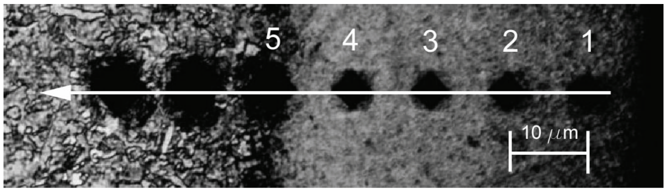

Figure 6. Microhardness Measurement Impressions on the Workpiece.

Impressions increase in size the farther they are from the border of the workpiece, which reinforces the notion that there is effective surface hardness variation towards the core of the workpiece. Table 2 and Table 3 show the results of microhardness resulting from the tests with coolant and without coolant, respectively.

Table 2. Results of microhardness after phase 3 with coolant.

Depth (mm)	Microhardness (MV) measured on the tests with coolant							Average
0.10	680	665	690	672	683	675	689	679
0.20	650	642	663	655	661	660	655	655
0.30	570	635	645	410	640	615	632	625
0.40	380	359	383	390	330	370	547	397
0.50	330	353	361	305	368	350	368	353
0.60	305	308	300	297	300	310	330	314

Table 3. Results of microhardness after phase 3 without coolant.

Depth (mm)	Microhardness (MV) measured on the tests without coolant							Average
0.10	653	658	669	651	658	661	643	656
0.20	630	625	632	610	636	635	590	623
0.30	360	372	381	320	344	343	545	381
0.40	353	350	359	305	329	320	310	332
0.50	305	305	305	291	301	305	282	299
0.60	293	290	305	291	300	290	282	293

The average microhardness values measured in the tests are shown in Fig. 7. Phase 3 workpieces ground with coolant can reach depths of 0.30 mm with more than 600 MV. And in phase 3 workpieces ground without coolant values of 600 MV or higher were found only in depths up to 0.20 mm, which are also significant for surface hardening purposes.

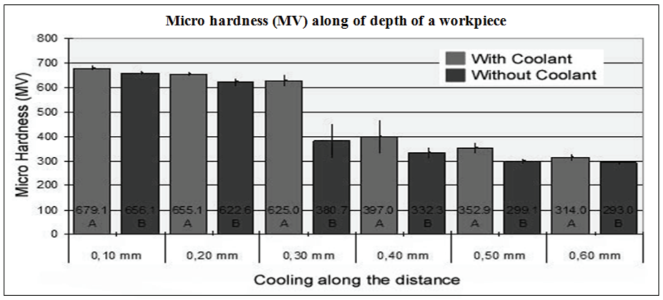

Figure 7. Average Values of Workpiece Micro Hardness Measures.

These microhardness differences along the depth of the workpieces can be explained by drawing an analogy with Jominy tests. Without the use of coolant, the workpiece cooling rate is lower and carbon diffusion in the workpiece structure is higher. As a result, a pearlitic phase (softer) is formed, and mixes to the martensitic and bainitic phases (harder than the pearlitic phase) at the sub-surface of the material. As for workpieces ground with coolant in phase 3, the workpiece cooling rate is higher and the pearlitic phase will only form in the deeper regions of the workpiece.

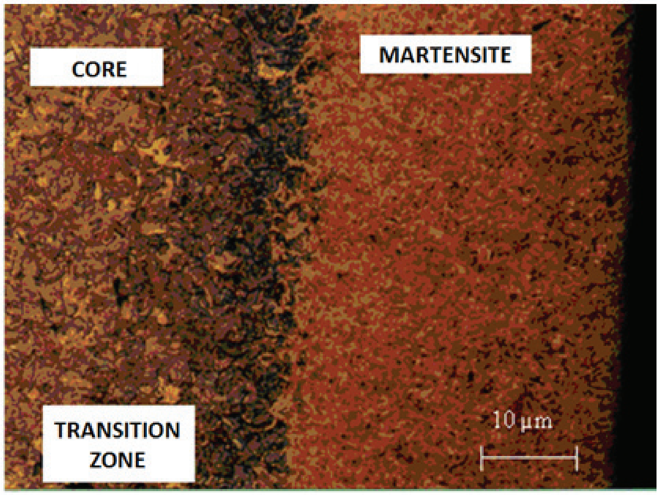

Figure 8. Cross Section of A Grind-Hardened SAE 4340 Steel Workpiece.

Microscopic analyses of the structure of ground workpieces as described above show that there is a transition region between the hardened portion and the core of the workpiece, as shown in Fig. 8.

In this transition zone there is an abrupt fall in micro hardness values, but the goals of the tests were not altered as a result of this fact. According to DIN 50190, the depth of an effective hardened layer runs from the surface to the point where hardness is at least 80% of its surface value. Figure 9 shows that the effective layers produced both with and without coolant, in phase 3, reach significant values of hardened depth: more than 0.30 mm for tests with coolant, and more than 0.20 mm for tests without it.

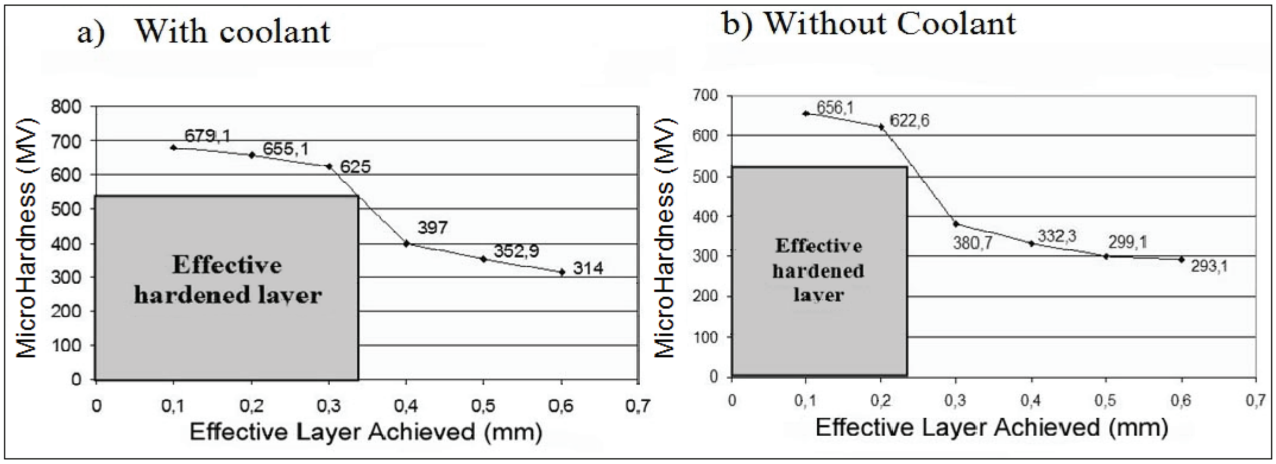

Figure 9. Effective Hardened Layer: a) With coolant in phase 3; b) Without coolant in phase 3.

Surface roughness

Measurements of surface roughness values were carried out twice during the tests: after phase 2 of the cycle (heating), and after phase 3 (finishing); in order to show the variation in the final results.

Table 4 shows the results after phase 2 and Table 5 shows the results after phase 3.

In phase 2, producing a finished surface was not required. Consequently, the average surface roughness values measured during the tests were higher.

Although these roughness values may be considered elevated for grinding operations, the values were acceptable for pre-finishing operations in both cases. The layer of material to be removed during the finishing operation (0.005 mm) is greater than the damage observed on the surface of the workpiece after phase 2.

Table 4. Results of roughness, in Ra (µm) after phase 2.

	Roughness Ra (µm) from the tests with coolant	Roughness Ra (µm) from the tests without coolant
	2.1	2.7
	2.3	2.5
	1.9	2.9
	1.9	2.7
	2.1	2.5
	2.3	2.8
	2.1	2.7
Average	2.1	2.7
StDev	0.16	0.15

In addition, the average roughness values obtained after the finishing phase were significantly lower than the ones obtained in the previous phases, and fall within the expected range for finishing grinding operations.

Table 5. Results of roughness, in Ra (µm) after phase 3.

	Roughness Ra (µm) from the tests with coolant	Roughness Ra (µm) from the tests without coolant
	0.9	0.8
	0.8	0.9
	0.9	0.9
	0.9	0.8
	0.8	0.9
	0.8	0.9
	0.9	0.9
Average	0.86	0.87
StDev	0.05	0.05

It should be pointed out that after the finishing phase of the cycle described above is completed, an additional grinding operation can be carried out in order to further reduce roughness or to achieve dimensional tolerances that were not achieved in the previous cycle.

Conclusions

The proposal of hardening SAE 4340 steel workpieces in grinding operations has been proven feasible. Thermal damages, including "grind burn", were not detected on the workpieces, but surface crack tests were not carried out.

The grinding cycle presented in this study produced surface hardness levels that were consistent with those achieved by electrical induction hardening. The effective hardened layers obtained in the tests were shown to be also consistent with to DIN 51190.

With regard to surface finishing, the roughness values obtained were the same as those in conventional processes, with hardening followed by a grinding operation.

The comparison between cycles performed with and without the use of a coolant shows that surface hardness and effective hardened layer results were better when a coolant was applied. As explained above, in the latter case the workpiece cools down in a shorter period of time and this leads to faster and deeper changes in the structure of the material. When the cycle is conducted without a coolant, the cooling is slower, and the pearlitic phase is formed earlier, mixing with the martensitic and bainitic phases in the sub-surface, and reducing the hardening process of the material.

References

Abrão, A.M., 1991, "Sistema para Avaliação de Desempenho Térmico de Pares Rebolo-Peça em Retificação" (System for Thermal Performance Evaluation of Peer-Part Grindstone in Grinding). São Carlos: EESC, USP. Dissertação de Mestrado (Mestrado em Engenharia Mecânica). Universidade de São Paulo, São Paulo.

Abrão, A.M., Aspinwall, D.K., 1996, "The surface integrity of turned and ground hardened bearing steel", *Wear*, Vol. 196. August, pp. 279-284.

Aguiar, P.R., Dotto, F.R.L., Bianchi, E.C., 2005, "Study of Thresholds to Burning in Surface Grinding Process", *Journal of the Brazilian Society of Mechanical Sciences & Engineering*, Vol. XXVII, No. 2, April-June, pp 150-156.

Aguiar, P.R., Serni, P.J.A., Dotto, F.R.L., Bianchi, E.C., 2006, "In-Process Grinding Monitoring Through Acoustic Emission", *Journal of the Brazilian Society of Mechanical Sciences & Engineering*, Vol. XXVIII, No. 1, January-March, pp. 118-124.

ASM International Handbook Committee, 1991. ASM Handbook, Volume 04 – Heat Treating. ASM International.

Brinksmeier, E., Heinzel, C., Wittmann, M., 1999, "Friction, Cooling and Lubrication in Grinding". In: Annals of the CIRP – Manufacturing Technology. Vol. 48. Issue 2, pp. 581-598.

Brinksmeier, E., Heinzel, C., Bohm, C., 2001, "Stabile Prozesse beim Schleifhärten", W+B Werkstatt und Betrieb, 134, pp. 46-50.

Brinksmeier R.E., Brockhoff, T., 1996, "Utilization of Grinding Heat as a New Heat Treatment Process", In: Annals of the ClRP, Vol. 45, Issue 1, pp. 283-286.

Brinksmeier, E., Garbrecht, M., Meyer, D., 2008, "Cold surface hardening", In: Annals of the CIRP – Manufacturing Technology, Vol. 57, pp. 541-544.

Brockhoff, T., 1999, "Grind-Hardening: A Comprehensive View", In: Annals of the ClRP, Vol. 48/71/7, pp. 255-260.

Callister, W. Jr., 2010, "Materials Science and Engineering: An Introduction", 8th ed., John Wiley & Sons, Inc., New York, NY.

Deutsches Institut Für Normung, DIN 50190: Hardness depth of heat-treated parts; determination of the effective depth of hardening after flame or induction hardening, 1979.

Dotto, F.R.L., Aguiar, P.R., Bianchi, E.C., Serni, P.J.A., Thomazella, R., 2006, "Automatic System for Thermal Damage Detection in Manufacturing Process with Internet Monitoring", *Journal of the Brazilian Society of Mechanical Sciences & Engineering*, VXXVIII, No. 2, April-June, pp. 153-160.

Gâmbaro, L.S., 2006, "Proposta de Otimização de Processos de Fabricação de Peças Cilíndricas por Meio da Têmpera por Retificação" (Proposal Process Optimization for the Manufacture of Cylindrical Parts by Means of Hardening by Grinding). Dissertação (Mestrado em Engenharia de Produção), 106p. – Faculdade de Engenharia Urbanismo e Arquitetura, Santa Bárbara d'Oeste.

Han, Z.T., Zhang, N.J., Gao, D., Yang, G., 2007, "Research into Grinding Hardening of Microalloyed Non-quenched and Tempered Steel", *Journal of China University of Mining and Technology*, Vol. 17, Issue 2, June, pp. 238-241.

Hou, Z.B., Komanduri, R., 2004, "On the Mechanics of the Grinding Process, Part II: Thermal Analisys of Fine Grinding", *International Journal of Machine Tools & Manufacture*, Vol. 44, pp. 247-270.

Klocke, F., Brinksmeier, E., Weinert, K., 2005, "Capability Profile of Hard Cutting and Grinding Processes", In: Annals of the CIRP – Manufacturing Technology, Vol. 54, Issue 2, pp. 22-45.

Lima, A., Vieira Junior, M., 2002, "Study of Macro and Micro Quality Determinants of Pieces Obtained from Optimized Drilling Process", In:

Sixth International Conference on Advanced Manufacturing Systems and Technology – AMST`02, Udine-Italy. Anais Of Sixth International Conference on Advanced Manufacturing Systems and Technology – AMST`02. Udine – Italy: Elso Kuljanic, 2002. pp. 179-185.

Lima, A., 2008, "Análise dos Efeitos Gerados Pelos Parâmetros de Corte em Processos de Usinagem Sobre a Integridade Superficial das Peças em Aço ABNT 4340" (Analysis of the effects generated by Cutting Parameters in Machining Processes On the surface integrity of parts in AISI 4340 Steel). Santa Bárbara D´Oeste: Programa de Pós-Graduação em Engenharia de Produção, Faculdade de Engenharia, Arquitetura e Urbanismo, Tese (Doutorado em Engenharia de Produção), Universidade Metodista de Piracicaba, 203 p.

Malkin, S., Guo, C., 2007, "Thermal Analysis of Grinding", In: Annals of the CIRP Vol. 56/2, doi:10.1016/j.cirp.2007.10.005.

Nguyen, T., Zarudi, I., Zhang, L.C., 2007, "Grinding-hardening with liquid nitrogen: Mechanisms and technology", *International Journal of Machine Tools & Manufacture*, Vol. 47, pp. 97-106.

Shaw, M., Jr., 1994, "Heat-Affected Zones in Grinding Steel". In: Annals of the CIRP, Vol. 43, Issue 1, pp. 279-282.

Webster, J.A., 2007, "Improving Surface Integrity and Economics of Grinding by Optimum Coolant Application, With Consideration of Abrasive Tool and Process Regime", Procedings of IMech, Part B: *Journal of Engineering Manufacture*, Vol. 221, pp. 1665-1675. DOI: 10.1243/09544054JEM804.