# Residual stresses in steels after heat treatments and grinding

J. Grum & P. Žerovnik
*Faculty of Mechanical Engineering*
*University of Ljubljana*
*Aškerčeva 6, 1000 Ljubljana, SLOVENIA*
*EMail: janez.grum@fs.uni-lj.si*

## Abstract

The investigation was carried out on tungsten-chromium-vanadium steel 80WCrV8 according to DIN standard intended for cold and hot work on which different heat treatment and machining procedures were applied. The results of the investigation were obtained by residual stress measurements on the basis of relaxation method and electro-chemical removal of the surface layer under analysis. The applications of grinding on hardened steel produces compressive residual stresses in the surface layer which range between 400 and 900 $N/mm^2$ in dependence upon the kind of the grinding procedure.

## 1 Introduction

In the last decade the focus of numerous investigations has been to build such an information system whose data files and software would enable the integration of the design and the manufacturing process. The results of all these activities should give a high quality product which would have the required life and reliability in operation and answer the demands of the market. A very important role in such an information system is ascribed to the databases on materials which should contain the following groups of characteristic data:

- Fundamental data on steels, their mechanical, physico-chemical and technological properties;
- Types of semi-manufactures with their shape and size program;
- Surface integrity of the workpiece and tool material;

- Tribological data on the tribological system inclusively the influence of the environment.

Systematic studies relating to the effect of different metal removal methods and various parameters within these methods on the resulting fatigue properties of surface layer have been underway for several years. This work has been covered by the general topic "Surface Integrity". This area of study includes two aspects. The first is "Surface Topography", which describes surface roughness and other features of surface geometry. The roughness of a surface affects many aspects of its behaviour and a variety of methods have been employed, each with considerable ingenuity, to assess and measure it. We shall see that it is not a straightforward matter to quantify roughness, especially if the aim is to use this quantitative assessment in predicting subsequent tribological behaviour. However, it would seem reasonable to suppose that roughness must be characterized by some information on heights normal to the mean plane of the surface together with some knowledge of the spatial distribution, or wavelengths, within the surface. We can thus classify the various methods available for topographical examination according the range of vertical heights and spatial wavelengths they can each differentiate. The second is "Surface Metallurgy", which includes a study of surface alterations, which may be produced by the machining process and their effects on the mechanical properties of the surface layer /1,2,3/.

To achieve the desired roughness and dimensional quality of a workpiece, in many applications after the hardening process a finishing operation is necessary. Nevertheless, the subsequent machining operation can lead to critical microstructure, residual stresses and hardness or microhardness changes, especially on the surface and subsurface layers.

Examples of the detrimental influence of residual stresses are: deformations of a workpiece, either caused by removing stress-affected layers or by introducing residual stresses during the machining process, decrease of the static and especially the dynamic strength, and the increase of sensitivity to stress corrosion cracking. On the other hand, compressive residual stresses can influence the dynamic strength positively.

The microhardness of a workpiece surface layer can be influenced in several ways. The chemical composition, the microstructure and especially the carbon content determines the hardness of the base material. An increase of hardness can be achieved by heat treatment as well as by mechanical treatment. A high hardness of workpieces is often desired in order to increase the strength, the wear resistance and the lifetime.

The following guidelines are offered as general concepts for achieving optimum surface integrity level:

- Minimise grinding distortion and surface damage by using gentle or low stress conditions during finish grinding;
- Modification of standard low stress grinding procedures aimed at increasing productivity should not be made careful experimental without work. It has

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



been shown that such compromises can be tolerated in the material without producing adverse residual stresses and/or microcracks;

- Frequent dressing of grinding wheels thereby maintaining on open and sharp surface will help to minimise surface damage due to grinding at all other conditions being held consistent;
- Cutting fluid, to be consistently effective must be continuously directed to the wheel / workpiece interface;
- Abrasive processing in general and finish grinding in particular must be accomplished under strict process control when being used for manufacturing various parts with lower residual stresses than a critical stress.

The purpose of this contribution is to present a description of surface integrity of the workpiece and tool material with special emphasis on the conditions after the application of heat treatment and grinding by measuring residual stresses /4/.

## 2 Experiment procedure

The investigations were carried out on a low-alloyed tungsten-chromium-vanadium steel for cold or hot work 80WCrV8 according to DIN standard, manufactured by Ravne Ironworks with internal designation OSIKRO Special.

Chemical composition of steel:

0.8% C - 0.4% Si - 0.4% Mn - 1.0% Cr - 2.0% W - 0.3% V.

The data on heat treatment:

| | |
|---|---|
| soft annealing | 720 ... 750°C |
| hardening | 860 ... 900°C |
| tempering | 150 ... 400°C |

The experiments were carried out in two ways:

- On industrial knives intended for industry of the size 381x65.5 x9.4 mm$^3$ and
- On specimens of the size 50x30x5 mm$^3$.

On the industrial knives the last two technological operations consisted of heat treatment (hardening/tempering) and precision grinding. The machining parameters were not known because the machining was carried out in the Ravne Ironworks who did not provide the necessary data. The preparation of the special specimens was necessary for the following reasons:

- Due to insufficient data on heat treatment and machining it is not possible to make an analysis which would enable us to set the conditions for optimum surface integrity;
- Due to the extreme difficulty of measuring residual stresses on the tip of the knife.

The specimens of the size 50x30x5 mm$^3$ were heat treated in the Laboratory for Heat Treatment at the Faculty of Mechanical Engineering in Ljubljana and then machined by grinding in the Ravne Ironworks in industrial conditions.

The following heat treatment procedures were carried out:

- Hardening from a temperature of 880°C and tempering at a temperature of 150°C or 300°C;
- Annealing with the purpose to remove internal residual stresses incurred during the preparation of the specimens.

The data on the conditions of grinding on specially prepared specimens:

- After the specimens had been heat treated, segment grinding was applied. The grinding segments were placed on a grinding head of a diameter 700 mm;
- For the grinding of hardened and tempered specimens soft grinding was applied because of the requirement that the grinding grains are selfdressing;
- These requirements were well met by the grinding segments labelled RAPOLD 8A60-H7B14;
- Each side of the specimen was ground by 15 strokes of the grinding head with the removal rate of 0.01 mm/stroke;
- For the grinding of the material in soft state harder grinding segments labelled 2B 24/16 manufactured by SWATY Maribor were selected;
- The first group of the specimens were ground in 10 strokes, and the second group in 18 strokes at equal depth of cut.

## 3 Effects of heat treatment and grinding on the magnitude of microhardness on surface layer

The investigation of grinding mechanisms have led to a description of what happens during abrasive - metal interactions and how the grinding energy is dissipated /5-8/. Excessive grinding temperature causes thermal damage in the surface layer of the workpiece. One of the most common types of thermal damage to be avoided is a workpiece burn. This phenomenon has been studied mainly for grinding of carbon and alloy steels, although it is also a problem for grinding of some other metallic materials. Visible workpiece burn with steel is characterised by bluish temper colours on the workpiece surface, which are a consequence of oxide layer formation. At the start of burning, the workpiece surface becomes rougher and the rate of wheel wear increases. There is also a tendency for increased adhesion of metal particles to the abrasive grains, thereby causing the grinding force to grow. Therefore, it has been found from microhardness distribution in the surface layer of hardened steels with visible burns that reaustenitization of the workpiece also occurs. Rehardening is a consequence of reaustenization followed by rapid cooling with martensite transformation. The process of grinding produces various mechanical and thermal effects on the specimen surface. One of the most important effects is microplastic deformation of material in the contact zone which causes hardening of the material in the surface or in the surface layer. Due to friction conditions between the grinding wheel and the specimen and due to the presence of a

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



coolant/lubricant, this effect is joined by the effect of microhardening and tempering of the surface layer. These changes which take place only in the thin layers directly under the surface are strongly dependent on the machining conditions and kind of material. A hardened or softened surface layer on the specimen can be very successfully identified by microhardness measurements. The basic requirement of microhardness measurement on the cross-section area is the shortest possible distance of the first measurement from the surface and an adequate density of measurements into the depth. Figure 1 presents microhardness "HVm" versus depth below the surface "z" [µm] for the particular locations on the industrial knife which are marked on the right side of the diagram. It can be noted that heat extraction due to quenching is the most intensive on location 1 and then on location 2 and 3, which in also confirmed by the results of microhardness measurements carried out at particular depths. The microhardness curves presenting the location 4 and 5 are significantly different from those presenting the measurement locations on the tip of the knife. On location 4 a lower microhardness is measured at the same depth as compared to location 5 due to heat transfer between the knife and the gripper. From the diagram presenting the distribution of microhardness along the cross-section of the knife it can be noted that hardness is the lowest on the tip of the knife 820 HVm, then in the middle of the cutting edge 760 HVm and then on top of the edge 720 HVm.

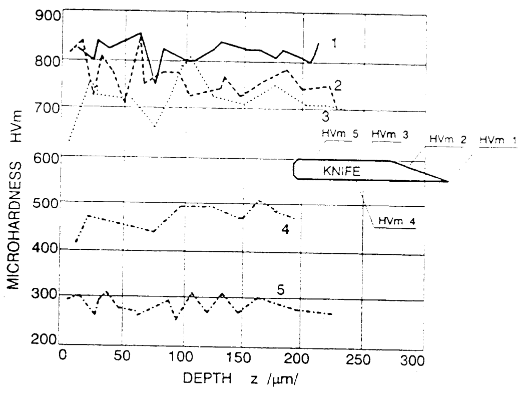


Figure 1: Microhardness curves for the particular locations on the cross-section of the industrial knife.

## 4 The effects of heat treatment and grinding on the magnitude of residual stresses

The grinding process invariably leads to residual stresses at/or near the finished surface, which can significantly affect the mechanical behaviour of the material. Therefore, residual stresses resulting from grinding have been extensively investigated. The literature on this subject has been reviewed by Brinksmeier

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



/10/. From the investigations described in this paper, a qualitative model for the heat generation and heat distribution in grinding with CBN and $Al_2O_3$ can be derived. The critical heat energy on the workpiece surface is defined where residual tensile stresses. It can be seen that this value will be exceeded when grinding with aluminium oxide. Using a CBN grinding wheel with a small grain size, the conditions are becoming even more favourable. As could be seen from the tangential forces are lower for small grain sizes which thus lead to a reduced amount of generated heat. The percentage of heat distribution into the grinding wheel and workpiece is principally the same, therefore the safety margin to the critical heat energy in the workpiece is even higher under this condition. Conventional testing methods such as metallographical inspection, X-ray diffraction, residual stress, and microhardness measurement are time consuming and cannot be used for testing. Therefore, there is a considerable need for non-destructive testing techniques /2, 11/.

In this study the identification of residual stresses was based on the relaxation method, which consisted in measuring workpiece deformation. The relaxation was induced by electro-chemical removal of the stressed surface layer, causing a breakdown in the existing equilibrium state. The restoration of the equilibrium was accompanied by workpiece strains /4/. The strains were measured by means of resistance strain gauges and calculated into stresses using a physical model.

The measurement system for measuring workpiece deformation after electro-chemical removal is shown in figure 2. In setting up the measuring system we have to solve the problem of the ratio between the useful and the disturbing signals. This ratio has to be at least ten times greater than the disturbing signal. The connections and charging of the measuring system have to be chosen to make the system sensitive to the smallest strains or changes in stresses.

Figure 3 illustrates the relationship between the measured strains and the calculated residual stresses. Computer software was designed to calculate the stress state in discrete points. Each residual stress was computed on the basis of the mean value for strain. The computations were made to the same depth as that of electro chemical removal, considering the size of the strains and the workpiece thickness.

On the basis of metallographic analysis, microhardness measurements in various depth layers, and residual stress measurements, instructions for the selection of conditions used in heat treatment and grinding of the discussed steel was prepared.

For the calculation of variation of residual stresses as a function of depth of flat specimens, it is necessary to know the time-dependent variation of the depth of electro-chemical removal. For each material we have to know the characteristics of electro-chemical material removal.

The speed of electro-chemical dissolving of specimens connected as anode depends on:

- anode current density $D_a$ [$A/cm^2$];
- size of the gap between the anode and cathode d [mm];

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



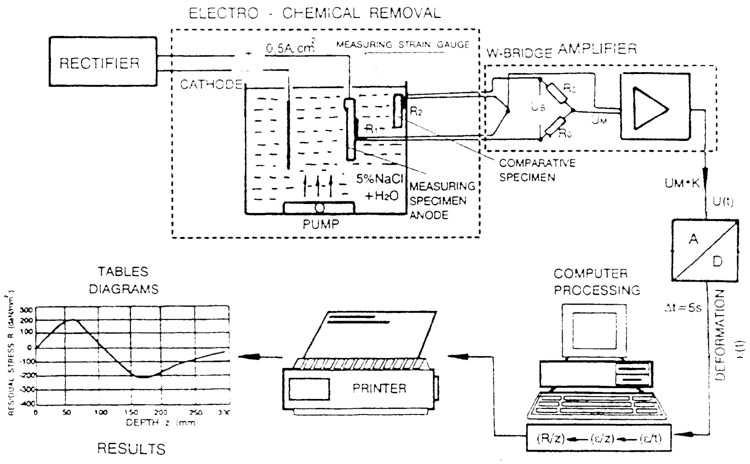


Figure 2: Measuring system for residual stresses measurements by relaxation method with electro-chemical removal of stressed surface layer.

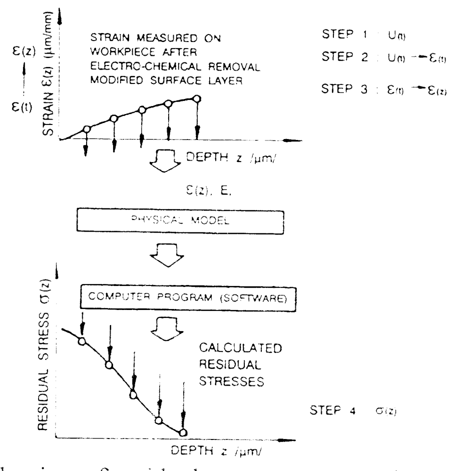


Fig. 3: The evaluation of residual stresses was made on the basis of measured strain.

- velocity of flow of the electrolyte between electrodes $v_{el}$ [m/s];
- voltage between the anode and the cathode $U_{ac}$ [V];
- type of anode metal.

Figure 4 shows the time variation t(s) of the depth of removal z (mm) in the chosen conditions of electro-chemical removal. The tests of electro-chemical dissolving of the material were made for a variety of machining conditions applied on the studied materials. From the figure we can see that the removal or electro-chemical dissolving of the material runs linearly with time, which makes the calculation of the depth at which the measured deformation is reached very simple. From this data we can then calculate the residual stresses as we know the change of the specimen cross-section and thus also the data about the inertia and resistance moment necessary for the calculation. From the data about the time-variation of the depth of electro-chemical removal, we can choose the most suitable conditions of the electro-chemical removal, namely:

- uniform material removal;
- suitable speed of removal;
- efficient disposal of anode products from the gap.

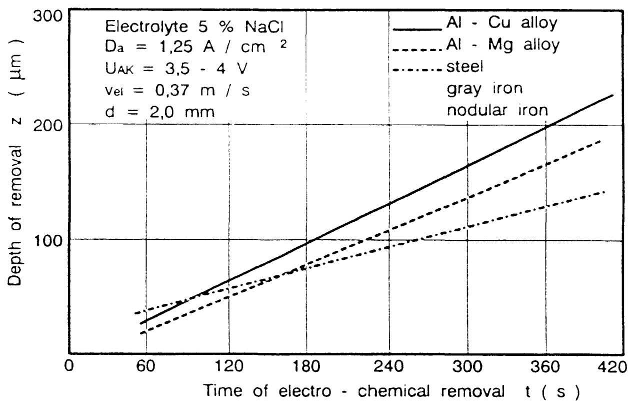


Figure 4: Variation of depth of electro-chemical removal in the given machining conditions.

Figure 5 presents the conditions on specimens after heat treatment, i.e.:

1c ... hardened and tempered $T_k = 880°C/T_p = 150°C$

2c ... hardened and tempered $T_k = 880°C/Tp = 300°C$

3c ... annealed $T_{?} = 650°C$

The ordinate in the figure presents the magnitude of residual stresses and the abscissa the depth on the specimen. The residual stresses are relatively low and of tensile nature. Low presence of residual stresses results form good hardenability of the steel and relatively small differences in the structural changes between the surface and the core. The conditions of heat treatment under 2c give maximum residual stresses of 130 N/mm$^2$ at a depth of 25 µm

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



whereas the conditions under 2c at a higher tempering temperature give slightly lower residual stresses of 110 N/mm$^2$. The correctness of the measured results in the heat treatment conditions given under 1c and 2c is confirmed also by the magnitude of residual stresses after stress-relief annealing at a temperature of 650°C (curve 3c). The magnitude of residual stresses after annealing is considerably lower and in the surface layer of a thickness of 0.15 mm ranges between 20 - 30 N/mm$^2$.

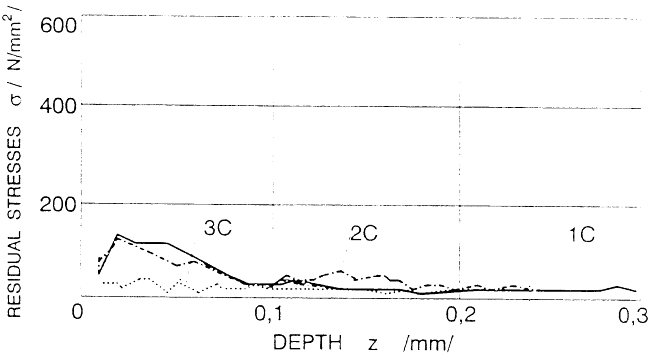


Figure 5: Residual stress curves for the specimens on which different heat treatment was applied

Another point of interest is to see what stress state changes are going on in the specimens which were differently heat treated and ground. From Figure 6 it is possible to establish the influences of grinding on the stress state changes of an annealed or soft steel in dependence upon depth. By its nature the grinding process causes considerable compressive stresses. In the experiment it was decided on two different numbers of strokes necessary to grind the specimen to the same size. By changing the thickness of the material removed in the particular stroke, rough grinding with 10 strokes (1D) and precision grinding with 18 strokes (2D) were obtained. The distribution and the absolute values of residual stresses are very similar in both cases and practically do not show any dependence on the thickness of the material removed by each stroke. The maximum residual stresses range between 320 and 350 N/mm$^2$ extending into a depth of 0.02 mm whereas the minimum residual stresses of some N/mm$^2$ are already found at a depth of 0.1 mm. In case of a harder workpiece material e.g. steel after hardening, the grinding of the surface layer produces additional thermal effects - structural changes and cold deformation effects - such as hardening of the material in softer subsurface layers. The segment grinding which was chosen for the experiment was carried out in 15 strokes when the process was accompanied by sparking (2E) and when it was not (1E). In the process without sparking, material removal is carried out in each stroke whereas with sparking, after a removal of 15 strokes, a few more strokes are made without plunging of the wheel into the depth. The process of spark grinding

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



enables the removal of tiny asperities, i.e. polishing and removal of volume particles containing higher residual stresses. From Figure 7 it can be noted that in a thin surface layer of a thickness of about 0.01 to 0.02 mm there is a significant difference in the absolute values of residual stresses. The process without sparking (1E) leaves residual stresses of about 900 N/mm$^2$ whereas the other process accompanied by polishing or sparking (2E) procudes residual stresses of about 400 N/mm$^2$. Regardless of the type of the grinding procedure, the resulting residual stresses are always of compressive nature producing a beneficial effect on the dynamical operating conditions.

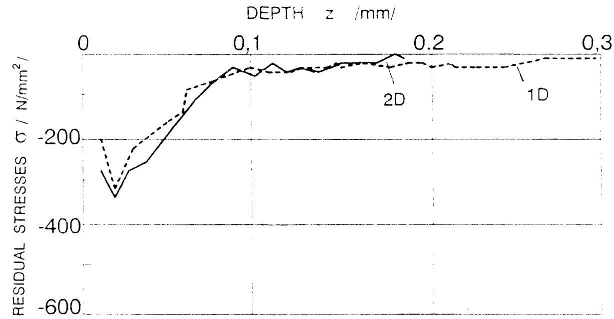


Figure 6: Residual stress curves for annealed specimens which were ground in 10 strokes (1D) and 18 strokes (2D).

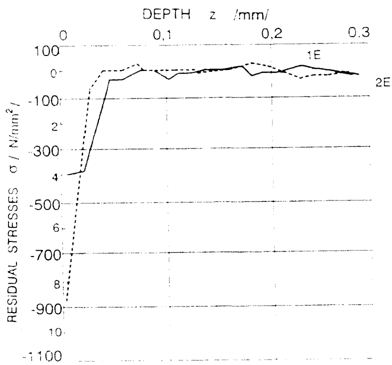


Figure 7: Residual stress magnitude versus depth below the surface after heat treatment and grinding without sparking (1E) and with sparking (2E).

## 5 Conclusions

The results obtained on surface integrity of tool and workpiece material clearly show the significance of research investigations in this field. Our discussion was limited only to those characteristics which result from microhardness and residual stress measurements, although there is a number of other experiments

Transactions on Engineering Sciences vol 17, © 1997 WIT Press, www.witpress.com, ISSN 1743-3533



which can contribute to a more thoroughful presentation of the surface state after the application of various machining procedures.

Grinding with slotted or segmented wheel, i.e. intermittent grinding, as one of effective ways to reduce grinding thermal damage and improve grinding performance, has been paid more and more attention and found utilisation in many applications.

From the case under investigation the following conclusions can be drawn:

In a steel which has been annealed residual stresses are extremely low ranging between 20 - 30 N/mm$^2$;

- In a steel which has been heat treated (hardened/tempered), residual stresses are of tensile nature, their magnitude ranging between 110 and 130 N/mm$^2$;
- The application of grinding subsequently to annealing causes compressive residual stresses in the surface layer which amount to about 360 N/mm$^2$ regardless of the depth of cut;
- The application of grinding on hardened steels produces compressive residual stresses in the surface layer which range between 400 and 900 N/mm$^2$ in dependence upon the kind of the grinding procedure. The procedure of segment grinding which was choseh for this investigation ensures that only compressive residual stresses are induced. Such a stress state is very beneficial because it prevents the occurrence and propagation of cracks. How efficient will such a mechanism be, however depends, besides on residual stresses, also on the conditions acting on the product in the loaded state.

An assessment of the influence of different grinding process parameters on the development of residual stresses is possible, at least qualitatively, if their consequence on the heat generation and plastic deformation in the surface layer of the workpiece in considered. The related material removal rate, very often used to characterise the grinding process, which is given by the product of the workpiece speed and the depth of cut, has no clear influence on the generated residual stress state.

Increasing the speed of the workpiece diminishes the local heating of the surface and hence shifts the surface residual stresses towards compression. Increasing the depth of the cut, however, supports the development of tensile residual stresses.

## Reference:


1. Field, M. & Kahles, J. F. Review of surface integrity of machined components, Annals of the CIRP, 1971, 2, 153-163.

2. Field, M. & Kahles, J.F. & Commett, J.T. A Review of measuring methods for surface integrity, Annals of the CIRP, 1972, 2, 219-238

3. Koster, W. P. Surface integrity of traditional machining processes, *Procedings of the Interantional Conference on Surface Technology, Carnegie Mellon University*, Pittsburgh, Pennsylvania 1973, 442-468.

4. Grum, J. & Žerovnik P. Residual stresses in tool steels after heat treatment and subsequent grinding *Proceedings of the 5th Yugoslav Symposium on Heat Treatment of Metals*, Vrnjačka Banja 1989, 289-293.

5. Malkin, S. Grinding of Metals: Theory of application, Journal of Applied Metalworking, 1984, January, 95-109.

6. Lindsay, R. P. & Hahn, R.S. On the basic relationships between grinding parameters. Annals of the CIRP, 1971, 1, 657-666.

7. Turley, D. M. Deformed layer produced by machining, *Proceedings of the International Conference on Surface Technology*, Carnegie Mellon University, Pittsburgh, Pennsylvania 1973, 39-52.

8. Scholtes, B. Residual Stresses introduced by machining, (ed. A. Niku - Lari) pp. 59-71 Advances in Surface Treatments, Pergamon Press, Oxford, 1987, 59-71.

9. Brinksmeier, E. A model for the development of residual stresses in grinding, Advanced in Surface Treatments, Technology - Applications - Effects, volume 5, (ed. A. Niku - Lari) pp. 173-189 Pergamon Press, Oxford 1987, 173-189.

10. Brinksmeier, E. Schneider, E. Theiner, A. & Tönshoff, H.K. Nondestructive testing for evaluating surface integrity, Annals of the CIRP, 1984, 2, 489-508.