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A review of the influence of grinding conditions on resulting residual stresses after induction surface hardening and grinding

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Abstract

Internal stresses which are, since the completion of manufacturing, termed residual stresses very much reflect the manufacturing procedures and machining conditions.

Residual stresses are analysed in terms of different induction surface hardening conditions and then also after finish grinding in terms of different machining conditions.

Induction surface hardening creates very desirable residual stresses in the hardened surface layer. Residual stresses are always of a compressive nature and are usually present to the depth of the induction-hardened layer. By the appropriate selection of grinding wheel and grinding conditions and taking into account the physical and mechanical properties of the workpiece material very favourable compressive residual stresses in the hardened surface layer can be retained.

How is it possible to assure a desirable surface and surface layer quality after induction-hardening and fine grinding? Finding an answer to this question requires a very good knowledge of the process of grinding on the micro-level as well as knowledge of mechanical and heat effects acting on the layer of the workpiece including the type and condition of the grinding wheel. An all-inclusive consideration of the numerous influences of the kind and condition of the tool on the changes on the surface and in the surface layer of the workpiece in the given machining conditions is described by the term "surface integrity".

Keywords: Residual stress; Induction surface hardening; Grinding; Grinding conditions; Grinding wheel

1. Introduction

In most applications, induction heating in used to selectively heat only the portion of the workpiece that requires treatment. This usually means that the process can be accomplished in a relatively short time and with high efficiency because energy is applied to the workpiece only where it is needed.

Induction surface hardening is applicable to axisymmetric or near axisymmetric machine parts in steel or cast iron which are being produced in substantial volumes. There are two basic techniques for induction hardening machine parts, 'single-shot' and 'scanning'. The former employs selective heating and quenching to harden a specific area or areas of the machine part in one operation. The latter is usually applied to harden progressively long, continuous sections, such as shafts and spindles. In this instance, the scanning inductor traverses the length of the section, heating only a relatively small area at any given time, and is followed closely by the quench arrangement which is often an integral part of the inductor [1,2,4,5].

It is very important for dynamically loaded machine parts that the total compressive stresses in the thin, most loaded surface layer are ensured. The total stresses are a sum of residual stresses in a machine part and of load stresses produced by the action of external forces and moments. In order to ensure a long life of the machine part, knowledge of the residual stresses in the machine part and how to adjust the size and distribution of the residual stresses by means of the selection of an appropriate production technology is highly important.

In surface hardening compressive residual stresses always occur in the thin surface layer due to martensite transformation. The size and variation of the residual stresses depend mostly on a carbon content and much less on the type and content of alloying elements in heat-treatment and surface-hardening steels. The variation of stresses in the surface layer can be varied by varying induction-heating conditions and by a quenching method.

Braisch [6] presented a model for a description of behaviour of dynamically loaded machine parts under different conditions of hardening and tempering as well as of surface

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induction hardening. The model developed is based on experimental data obtained with torsion-bending loads and allows optimisation of the conditions of surface induction hardening in terms of fatigue resistance. In recent technical literature, various models for an analytical description of heating can be found. They take into account a mutual physical dependence of a magnetic field and a microstructure as well as mechanical properties of the steel treated in order to determine thermal cycles at the surface and in the material as well as transformation and thermal stresses occurring during heating and quenching. The same physical models permit the determination of the size and variation of residual stresses in the surface layer after surface induction hardening [7–11].

Melander [7] analytically monitored the time variation of axial stresses during single-shot surface induction hardening and determined also the distribution of residual stresses after hardening. The same calculation was suitably supplemented also for progressive induction heating and quenching.

Denis et al. [8] proposed an analytical model to describe the temperature/time variation in surface induction heating and quenching. They proposed a so-called metallurgical and mechanical model for the determination of the portion of microstructure phases, the stress condition during heat treatment and the variation of residual stresses and hardness in the surface layer after heat treatment, respectively.

Raniecki et al. [9] extended the analytical model of Melander [7] for progressive surface hardening including surface induction heating and quenching with a differential equation for the description of pearlite–austenite transformation instead of using the conventional Johnson–Mehl equation. The authors verified the analytical model by applying it to a hollow cylinder with a description of a momentary thermal field in order to determine varying of individual components of internal stresses as a function of cylinder radius and cylinder length, respectively. Axial stresses were considered at the outside and the inside of the hollow cylinder. Inoue et al. [10], however, treated varying of a thermal field at a tooth of a gear wheel at a single or dual frequency in order to ensure as weak as possible distortion of the teeth, i.e. of the gear wheel as a whole, and as high as possible compressive residual stresses in the surface layer.

Longeot et al. [11] described mathematical relations between the created electro-magnetic field in the workpiece material and the thermal phenomena occurring in it. Thus a picture of the thermal field in the surface layer of the workpiece was obtained. If changes of individual microstructure phases during heating and quenching as well as temperature variation of mechanical properties are known, such a picture permits an on-line analysis of strain and stress conditions. The model proposed also permits the prediction of the final size of strain and the size and distribution of residual stresses after heat treatment. The paper states the results of the simulation performed. The latter provide quite a good insight into the heating and quenching processes going on in different workpieces under different heating and quenching conditions.

Different experimental methods have to be used due to a particularly exacting physical description of induction surface heating and quenching. The ones are used for measurement of strains and the others for measurement of residual stresses. For the measurement of residual stresses, destructive testing methods are prevailing. They can be applied directly to machine parts or to specimens adapted to the purpose. The destructive methods are characterised by relaxation of the stressed layer at the machine part or the specimen. The residual stress is then calculated from the measured strain. Lately, the method of X-ray diffraction at crystal lattices has been used predominantly. It permits determination of relative changes of the crystal-structure parameter. Then the size of residual stresses at the micro-level can be calculated.

In practice, experiments are often performed on specimens of a suitable shape and size and made of the given material. These specimens are then surface induction hardened with different heat inputs and at the same or different current frequencies. Such studies indicate the relation between individual parameters of heat treatment and the size and variation of residual stresses [12,13]. In industry, technologists control quality of a machine part after surface induction hardening and fine grinding by measuring the thickness of a hardened layer and determining the hardness obtained in the hardened layer by various non-destructive testing methods. One such method is the eddy-current method [14]. Another very efficient method of quality control is measurement of strain after hardening of the machine part and straightening of the machine part prior to fine grinding [15]. In any case final grinding, i.e. grinding to size, is necessary and often results in huge costs due mainly to grinding additions. Grinding additions themselves depend on the expected size of strain after surface hardening and the efficiency of straightening of the machine part. A suitable grinder and adapted grinding conditions should be selected for final grinding. Moris and Snoeys [16] gave first a critical review of literature in terms of heat generation in the grinding process. In this connection they explain microstructural changes and, consequently, also residual stresses and microhardness after grinding the selected material in the thin surface layer. In the second part they focus on representation of various theoretical and experimental thermal models in grinding. They relate them to microstructural changes and, consequently, with a change of hardness and residual stresses.

Tomlinson and coworkers [17,18] treated, in two papers, formation of a some micrometers thick white layer in the thin surface layer in very coarse grinding processes in terms of surface roughness and different damages to the surface as well as microstructural changes and the variation of microhardness and residual stresses in the surface layer.

Brinksmeier [19] presented numerous experimental results obtained in grinding of hardened steel under various grinding conditions and with different kinds and grain sizes of the grinding material in terms of force measurement, grinder wear with regard to material removal from the workpiece during the grinding process, as well as in terms of residual stresses in the thin surface layer. The experimentally measured variations of residual stresses were compared with the variations of residual stresses calculated by means of FEM programmes ADINA and ADINAT. 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 by tensile residual 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, 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.

Walker [20] in his paper treats changing of residual stresses and hardness in the surface layer after surface induction hardening and the total residual stresses after hardening and final grinding. The final fine grinding was carried out under different grinding conditions so that microstructural changes occurred in the cold workpiece material due to friction heat generated in the contact zone and to heat conduction. The microstructural changes are accompanied by volume changes, which results in changes of the size and variation of residual stresses through the thickness which slightly exceeds the depth of the heat affected zone.

Mahdi and Zhand [21] proved, with the method of final elements, that compressive residual stresses after surface induction hardening are almost independent of a quenching agent if the latter ensures at least the upper critical quenching rate. Another very important finding is that during the grinding process, also phase transformation occurs in the thin surface layer due to friction heat, which in almost all cases produces tensile residual stresses due to grinding.

2. Main feature of induction hardening

One of the main features of induction heating compared with conventional heating procedures is that heat is generated in the workpiece itself. In conventional heating procedures the heat input achieved is only 5–200 kJ/m^2 s energy, whereas in induction heating this energy input is 300 MJ/m^2 s. In induction heating, heat penetrates into the workpiece by the aid of high frequency alternating current, the choice of frequency depending on heating requirements. Induction heating power supplies are frequency changers that convert the available utility line frequency power to the desired single-phase power at the frequency required by the induction heating process. They are often referred to as converters, inverters, or oscillators, but they are generally a combination of these. The converter portion of the power supply converts the line frequency alternating current input to direct current, and the inverter or oscillator portion changes the direct current to single-phase alternating current of the required heating frequency.

Many different power supply types and models are available to meet the heating requirements of a nearly endless variety of induction heating applications [2,3]. The specific application will dictate the frequency, power level (Fig. 1), and other inductor parameters such as coil voltage, current, and power factor (cos φ) or Q factor.

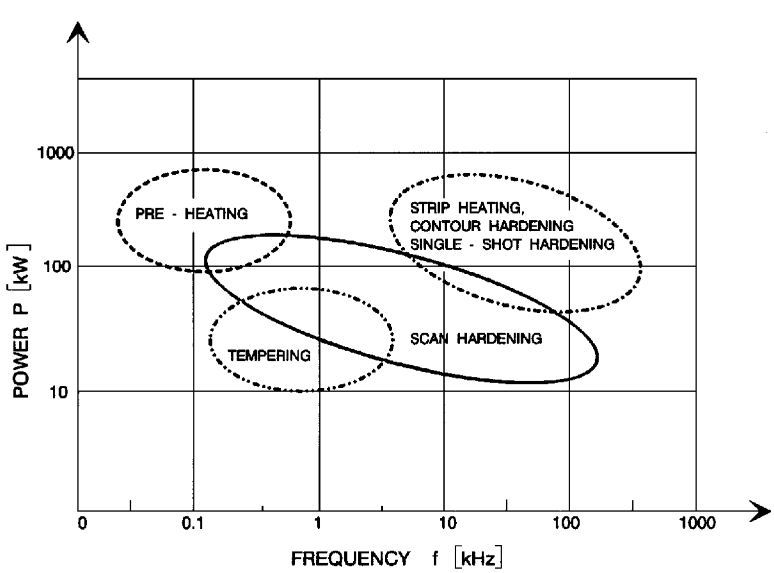

Fig. 1. Typical power–frequency regions of induction heat treatment applications.

Induction hardening is most often used for surface hardening of machine components and has the following advantages over other procedures [1,2,5]:

- Relatively short heating up times.
- Heating procedure is not strictly governed by hardening temperature. All that matters is that the heating process is not at too low a temperature as sometimes is necessary for the transformation into austenite. Upwards the temperature of heating is limited by the solidus-line temperature since the process is to be carried out while the material is in the solid condition. Due to a short heating up time, there is no danger that at higher autenitisation temperatures the austenite grains would grow, which also means that there is no danger of formation of coarse and brittle martensite.
- The quenching procedure is easy to perform contributing to short surface hardening times. In progressive induction hardening, right beneath the inductor, a spray coil is located directly performing the quenching of the heated surface. In single-shot hardening, the inductor is designed so that it performs the function of heating as well as quenching. The coil around the workpiece functions as inductor in the phase of heating and after the austenitisation temperature has been reached, the current is interrupted and the coil starts functioning as a spray for quenching.
- Induction hardening is a short procedure not requiring any additional protection against oxidation. Thus compared with other similar procedures such as cementation, it does not require much subsequent machining.
- Thanks to the nature of the procedure, after induction hardening the workpieces especially if shaped symmetrically are less susceptible to undesirable deformations. The volume changes in the workpieces after hardening the surface layer can be very accurately predicted or estimated. The volume changes after induction hardening of thin layers are so small that quite often the function of the machine component is not affected.
- Especially in induction hardening of thin layers and workpieces with low mass it is possible to achieve the desired critical rate of cooling by self-cooling in air alone, i.e. by heat conduction from the heated surface layer into the remaining cold part of the workpiece. With thicker layers and workpieces of greater mass, it is necessary to use such quenching agents that move the actual cooling rates close to the critical cooling rate. These requirements can be met with a right selection of quenching oils or polymer water solutions. Practical experience has shown that polymer water solutions are very suitable for quenching of induction-heated surface since with the right choice of concentration of the polymer water solution optimal quenching can be ensured.
- The induction hardening procedure enables the engineer, by simply adapting the shape of the induction coil, to ensure a desired shape of the hardened profile of the surface layer. Likewise, the engineer can surface harden only that part of the surface (local hardening) on which a certain increased level of hardness and wear resistance are wanted. One of the main advantages of induction hardening is that it makes possible to harden a surface layer only on certain places, at defined penetration depth and shape.
- These advantages make it possible that the induction hardening can be fully automated and is especially suitable for large series of workpieces.
- Induction hardening always leaves compressive residual stresses in the surface layer which makes machine components more resistant to dynamical loads. Compressive residual stresses in the surface layer after induction hardening reduce the occurrence of cracks in dynamically loaded components and reduce the growth of existing cracks on the workpiece surface if these are present due to hardening or hardening and grinding.
- Induction hardening is appropriate for small-sized workpieces since by well chosen technology of heating and cooling or quenching we can ensure a hardened surface layer and a refined core. Thus we can create a required wear resistance of the machine component on a certain location as well as required load bearing capacity of the component suffering only a slight loss in toughness of the core.

3. Experimental procedure

3.1. Workpiece material and manufacturing crankshaft

For manufacturing crankshafts a heat-treatable steel 4140 according to AISI standard, was used. This steel is very appropriate for dynamically loaded machine parts of car engines and machines especially because of its high tensile strength after quenching and tempering. The steel is characterised by good hardenability and is thus suitable for manufacturing parts with large cross-sections in which after refinement a very high strength can be obtained. After tempering, the steel does not show a tendency to brittleness and therefore no special heat treatment procedures are required. This steel is also suitable for flame or induction surface hardening and displays a very good resistance to wear. However, special attention has to be paid in the phase of product design and great care should be given to the design of radius and transition areas to prevent notch effects under dynamical loads. The steel is adapted for the use in a wide range of temperatures and preserves high toughness even at low temperatures.

Table 1 presents the chemical composition of structural heat treatable steel 4140 according to AISI standard. The steel contains between 0.38–0.45% carbon, 0.90–1.2% chromium and 0.15–0.30% molybdenum. It has very high hardenability, contributing to high strength values also in products with high mass. Molybdenum yields a desirable fine microstructure after hot working as well as heat treatment contributing to a good strength-to-toughness ratio. Thanks to its fine-grained microstructure it also reaches a relatively high toughness in the heat-treated conditions.

Table 1
Chemical composition (%) of quenched and tempered structural steel 4140 according to AISI standard

C	Si	Mn	Cr	Mo	P_{max}	S_{max}
0.38–0.42	0.15–0.40	0.50–0.80	0.90–1.20	0.15–0.30	0.035	0.035

Table 2
Mechanical properties of heat-treated structural steel 4140

Diameter D (mm)	Yield point $R_{p0.2}$ (N/mm^2)	Tensile strength R_m (N/mm^2)	Extension A_5 (%)	Toughness ρ_3 (J)
$16, \ldots, < 40$	769	$980, \ldots, 1180$	11	41
$40, \ldots, < 100$	635	$880, \ldots, 1080$	12	41

Table 3
Fatigue strength of structural steel 4140 after quenching and tempering at different temperatures

Diameter D (mm)	Fatigue strength			
	Tensile strength R_m (N/mm^2)	Bending σ_B (N/mm^2)	Compression–tension σ_{C-T} (N/mm^2)	Torsion σ_T (N/mm^2)
$16, \ldots, < 40$	$980, \ldots, 1180$	470	375	285
$40, \ldots, < 100$	$880, \ldots, 1080$	430	345	255

The strength of the steel concerned as well as its surface hardness and consequently wear resistance may be increased by heat treatment and thermochemical treatment. Mechanical properties of steel having diameter of up to 40 mm and between 40 and 100 mm are given in Table 2. Tensile strength of the steel concerned varies between 880 and 1080 N/mm^2 and a minimum toughness value ρ_3 amounts to around 41 J. The steel is very sensitive to notch and transition on machine parts subjected to fatigue loading. Table 3 gives values which are a basis of evaluation of fatigue strength for various loading conditions. Fatigue strength of the material is lowest under torsional load σ_T and varies, for the diameters mentioned, i.e. 16–40 mm, is $\sigma_T = 285\,\text{N/mm}^2$ and for diameters greater than 40 up to 100 mm is $\sigma_T = 255\,\text{N/mm}^2$. Fatigue strength under torsional load is three or four times lower than the tensile strength of steel under static load according to the data in the tables.

Fig. 2 presents the crankshaft formed by hot forging and Fig. 3 shows manufacturing procedure from blank to crankshaft. The procedure of forming should be carefully prescribed including the initial and final temperatures of forging

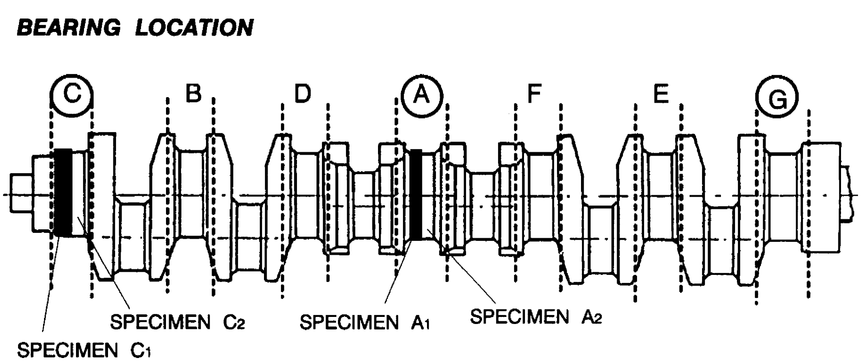

Fig. 2. Schematic presentation of crankshaft and marking main bearing locations.

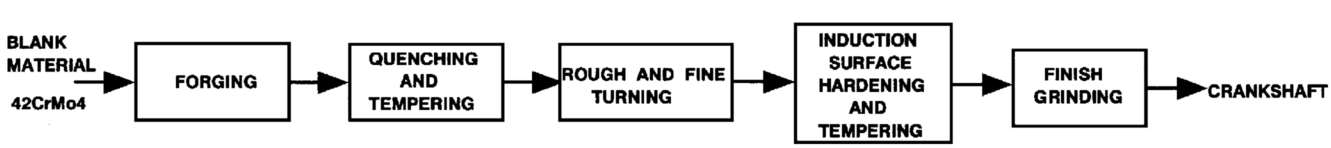

Fig. 3. Manufacturing procedure from blank to crankshaft.

and the uniform plastic deformation rate for the entire volume. This is followed machining procedures of turning and grinding with the purpose to approach the final dimensions of the product. The technology of manufacturing the crankshaft involves careful selection of the conditions of turning and subsequent grinding to avoid the negative occurrence of tensile residual stresses that would remain in the material even after induction surface hardening and would thus reduce the fatigue strength of the material. Induction surface hardening may be preceded by stress annealing if the depth of the surface hardening is smaller than the depth of the damaged layer, since in this way it is possible to change the unfavourable stress state in the surface layer induced by machining. In our case, the depth of the induction surface hardening was greater than the depth of the damaged surface layer, therefore machining could immediately be followed by induction surface hardening. However, it is necessary that after induction surface hardening the size and distribution of residual stresses are made such that they contribute to toughness and fatigue strength of the material. In our tests, the induction surface hardening was followed by finish grinding and non-destructive magnetic testing of the surface layer to reveal possible existence of cracks on the product's.

3.2. Conditions in induction heating and quenching of machine parts

Heating of workpieces is done so that in the inductor which is connected to a high frequency generator creates a magnetic field. When a ferromagnetic material or workpiece is introduced into the magnetic field, eddy currents are induced in it. The distribution of eddy currents in the workpiece is specific, their density being highest on the surface and falling towards the inside. This phenomenon is known as the surface effect or skin effect. Due to resistance offered by the workpiece material, heating takes place mostly in the thin surface layer, whereas the inner core remains cold or is only slightly heated (low-mass workpieces).

The penetration depth of the surface layer, i.e. hardened layer is the smaller, the lower is the specific electrical conductivity, and the higher is the magnetic permeability of the workpiece material and the higher the frequency of the current. In heating, specific electric resistance rises with temperature and is even 5–6 time bigger than in the beginning. On the other hand, the magnetic permeability of the workpiece material falls with increase in temperature. The drop in magnetic permeability of steels depends on the temperature line A_2 where steel transform from magnetic into non-magnetic ferrite. The effect of the change of magnetic permeability on line A_2 is the bigger, the smaller the C content in the steel (the bigger is the proportion of ferrite in the steel) and vice versa. Due to rapid heating, the phase transformation moves upwards towards higher temperatures. The temperature/time curves of heating along the depth of the cylindrical component depend on the kinetics of the magnetic transformation A_2 and effects of other phase transformations during induction heating. The thickness of the hardened layer depends among other things also on the size of the gap between the inductor and the workpiece surface. In hardening with a high frequency current, the hardened layer thickness ranges between 0.5 and 1.0 mm, and in hardening with a medium frequency current a thickness of 1.0–1.5 mm is reached. The temperature time variation over the cross-section of the steel workpiece is a function of the following factors: penetration depth of eddy currents, heat conduction of the material, heating rate of the surface, initial temperature of the surface, size and shape of the workpiece [1,4,5].

The depth of penetration of the heat is governed mainly by the power and frequency employed. The normal power density is 0.1–2 kW/cm^2 of the heated surface. The relationship between depth of penetration and frequency can be calculated approximately by using simplified expressions, which are valid for the temperature rise in steel up the hardening temperature [22]:

$$d_{hs} = \frac{20}{\sqrt{f}} \quad \text{cold state } (20^\circ\text{C})$$

$$d_{hs} = \frac{500}{\sqrt{f}} \quad \text{hot state } (800^\circ\text{C})$$

where f (Hz) is the frequency, d (mm) the depth of penetration.

Owing to heat conduction in the material during heating, the overall depth of penetration is larger. Is it possible to calculate the additional penetration due to heat conduction from expression:

$$d_{hc} = 0.2\sqrt{t}$$

where t (s) is the time, d_{hc} (mm) the depth of penetration.

The total depth of penetration is obviously $d_T = d_{hs} + d_{hc}$. It should be stressed that these expressions give only a rough estimate of the depth of penetration and they have been included here only to show the fundamental effects of frequency and time.

In flame heating the temperature achieved on the surface at equal energy input is considerably higher than in induction heating, the overheating and the hardened layer thickness being dependent on the heat conduction of the workpiece material. In Fig. 4, we can see the temperature time variation over the cross-section of the workpiece in flame heating. Characteristic of this variation is that the temperature rapidly changes with time and therefore the conditions for the formation of homogeneous austenitic microstructure are not fulfilled.

In Fig. 5, we can see the temperature time variation over the cross-section of the workpiece in induction heating. It can be noted that the temperature variation is very similar to that in flame heating up to magnetic transformation, i.e. to line A_2. At temperatures higher than line A_2, eddy currents

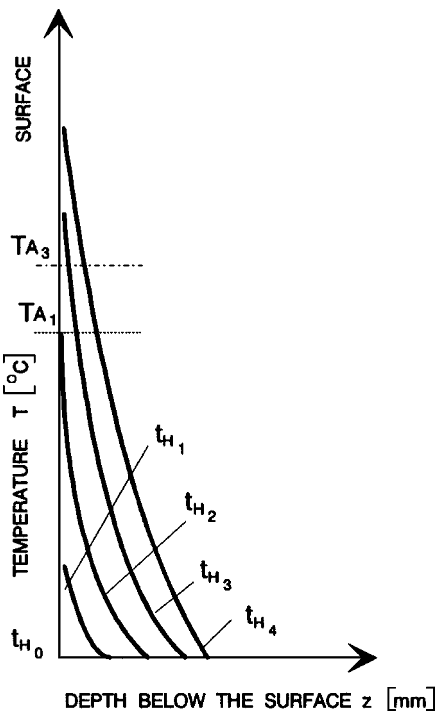

Fig. 4. Temperature profile in subsurface at various heating time in flame surface heating.

grow characteristically and the rate of heating decreases sharply. This slows down the heating above the temperature line A_2. Reduced rate of heating on the surface provides the conditions for faster heating into the depth of the workpiece. From the figure we can see that a relatively thin layer is

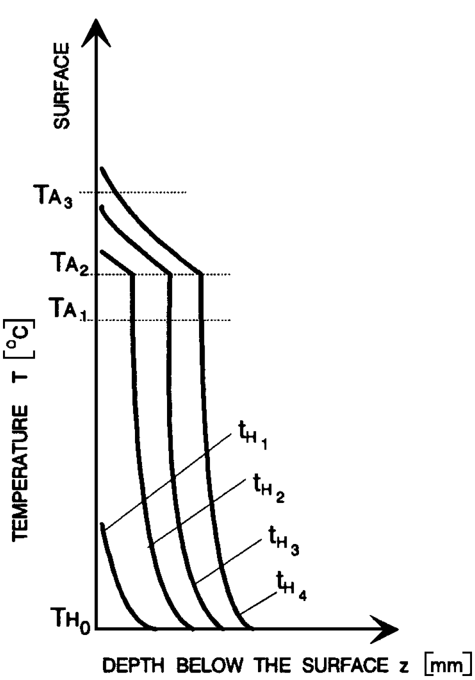

Fig. 5. Temperature profile in subsurface at various heating time in induction surface heating.

heated up but this layer has a rather homogeneous austenitic microstructure. The temperature time variation on the workpiece cross-section, or the temperature field, depends on the workpiece size and shape. Thus in heavy-mass workpieces, faster heat abduction into the remaining cold part of the workpiece is achieved and that is why the actual variation of temperature over the cross-section is steeper. This means that in heavy-mass workpieces, a higher temperature on the surface has to be ensured than in low-mass workpieces in order to grant the same penetration depth.

The microstructural changes in induction hardening depend to a large extent on the rate of heating and subsequent cooling. The rates of heating range from one to a few seconds, which means that the diffusion processes might get jeopardised. It is known that in steel transformation of pearlite into austenite takes place in induction heating at almost the same temperature as in conventional heating. In subeutectic steels suitable for surface hardening it is important that for transformation of ferrite into homogenous austenite the induction heating procedure ensures enough time for the diffusion of carbon.

3.3. Residual stress profiles after induction surface hardening

Internal stresses are induced in heat treatment by temperature and microstructure changes. Residual stresses in the induction surface hardened layer are always of compressive nature and are relatively high and have a good effect in dynamically loaded components. Very important is the existence of residual stresses in the radial direction, i.e. into the depth of the hardened layer. Importance is attributed also to the absolute value of residual stress on the surface and the stress profile in the transition from compressive into tensile stresses (Fig. 6). In the cases of induction hardening a maximum compressive residual stress in the surface layer is achieved, being very desirable for dynamically loaded components. The transition from compressive into tensile stresses should be as gentle as possible lessening the effect of stress concentration in loaded components. This contributes to the fact that a machine component is less susceptible to overloads in operation. It has been shown that residual stresses are closely linked to hardness variation and microstructure in the transition zone of the hardened layer, i.e. in the narrow range between the hardened and not hardened microstructure. Some examples of the dependence between the microhardness and residual stresses are shown in Fig. 7. In Fig. 7A, we can see a very steep microhardness profile in the transition zone and the highest compressive stress in the surface, and related to this, a very steep transition of residual stresses into tensile range. The change from compressive stresses into residual happens on the place of transition between the hardened and not hardened area. Fig. 7B and C shows graphs of broader transition zones which produces a change in the microhardness and also residual stresses. Thus in Fig. 7C for the same microhardness on the surface we can

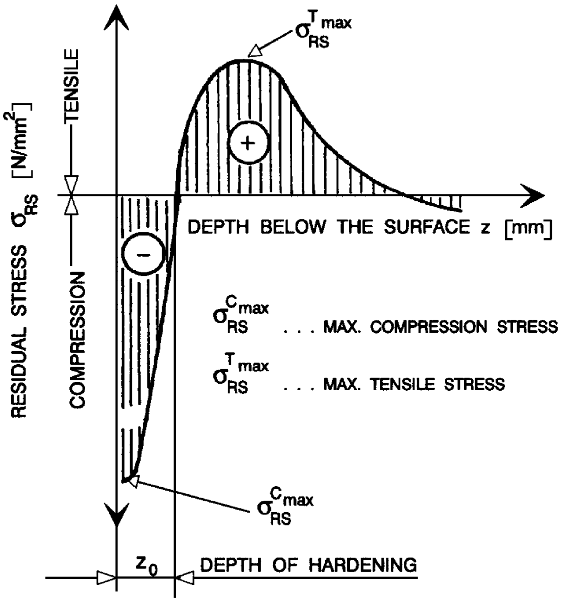

Fig. 6. Residual stresses profile below the surface after induction surface hardening.

note a very slight drop in hardness in the transition zone. This is reflected in lower compressive stresses in the surface accompanied by a slight change of stresses in the transition zone into lower tensile residual stresses. It has proved that in induction surface hardening the engineer should choose the kind of heat treatment conditions that will result in the microhardness and residual stress profiles as shown in the last two cases.

Investigations of residual stresses after induction surface hardening have confirmed that when the hardened layer is 2 mm thick, the change of compressive into tensile stresses happens in compliance with the transition zone, i.e. the achieved depth of the hardened layer. When the thickness of the hardened layer is greater than 2 mm, the transition from compressive into tensile stresses happens in the hardened zone, i.e. martensite microstructure. This means that induction surface hardening is much more difficult if the thickness of the layer is above 2 mm. Due to intensive cooling, the internal stresses in the surface layer may become so high that they cause failure of the component. This failure is very typical as due to high radial stresses the surface layer separates from the core. Important features on the curve are:

- maximal value of compression residual stress in the hardened surface layer;
- maximal value of tension residual stress in the hardened surface layer;
- transition width of compression to tension of residual stress in the hardened surface layer;
- transition steepness compression to tension of residual stresses profile;
- layer depth with transition microstructure.

3.4. Measuring and analysis of residual stresses after induction surface hardening and finish grinding

3.4.1. Method of measuring residual stresses

In this study the identification of residual stresses was based on the relaxation method which consisted in measuring specimen strain. The relaxation was induced by electrochemical removal of the stressed surface layer, causing a breakdown in the existing equilibrium state. The restoration

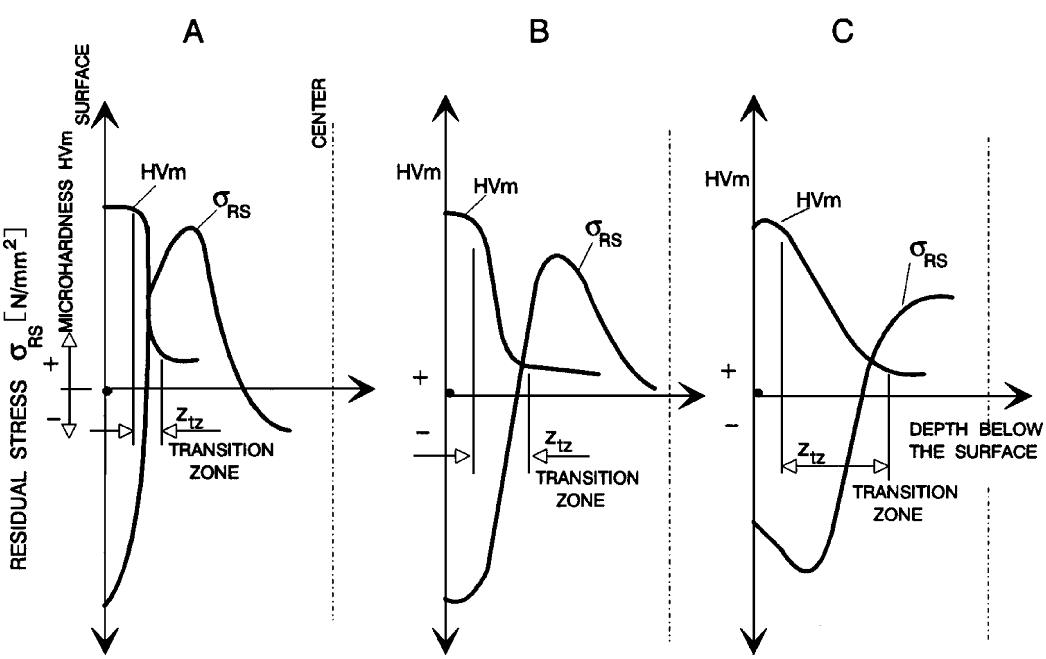

Fig. 7. Various types of residual stress and hardness profiles below the surface after induction surface hardening.

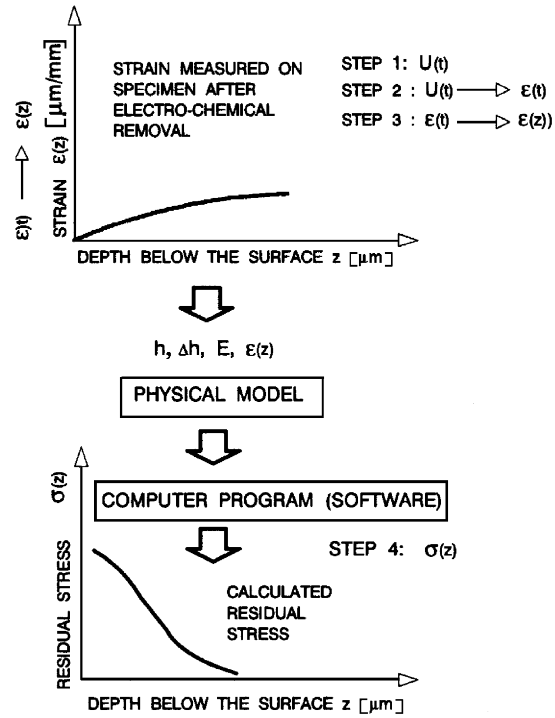

Fig. 8. The evaluation of residual stress was made on the basis of measured strain.

of the equilibrium was accompanied by specimen strain and residual stress. The strains were measured by means of resistance strain gauge and calculated into residual stresses using a physical model.

Fig. 8 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 value of 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 strain and the specimen thickness.

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

- type of anode metal;
- the gap between the anode and cathode d (mm);
- flow velocity of the electrolyte between electrodes v_{el} (m/s);
- current density D_a (A/cm^2);
- voltage between the anode and the cathode U_{ac} (V).

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 strain is reached very simple. From these 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 rate of removal;
- efficient disposal of anode products from the gap.

A right composition and microstructure scale of the particular phases in the surface hardened layer are important in defining the optimal properties in machine parts.

3.5. Analysis of residual stresses after induction hardening

Crankshafts were taken from production after induction surface hardening with the heat treatment and machining conditions as specified in the technology sheet. The residual stresses on the main crankshaft bearings were measured on the bearing location in the middle (A) and the extreme left side (C).

Fig. 9 shows the residual stress distribution after induction surface hardening in the central bearing location (A) and on the extreme left side (C). For both location residual stresses were measured on two samples. The distribution of residual stresses on the location (A) is as expected very similar on both samples, the highest compressive stress ranging between 1020 and 1060 N/mm^2 in the depth around 250 µm and then slowly dropping to a depth of 3.5 mm.

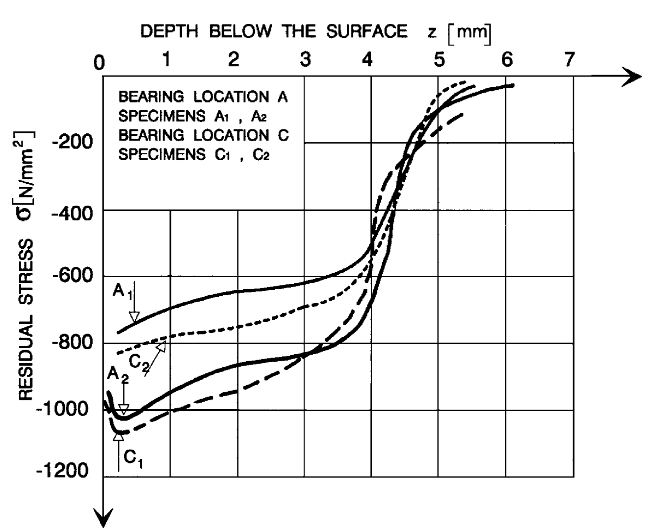

Fig. 9. Residual stress profiles after induction surface hardening on the specimens A_1 and A_2 of the mean bearing location in the middle of the crankshaft and on the specimens C_1 and C_2 on the extreme left side.

The residual stresses distribution after induction surface hardening on the bearing location (C) is very similar to that in the central bearing location (A) only that its absolute values are slightly lower and that a distinct fall in the residual stresses can be noted as early as around the depth of 3 mm reaching its minimum value already at a depth around 5.0 mm.

It can be seen that the residual stress distribution is just as favourable as in the central location only that its absolute values are slightly lower. Our belief is that the difference in the residual stress distribution can be related to the period of overheating on the austenitisation temperature which resulted in a thinner layer in austenitisation and thus also a thinner hardened surface layer.

3.6. Hardness in induction surface hardened layer

The induction surface hardened layer was analysed also by measuring the hardness and microhardness and their relations to microstructure. Since we wanted to establish some relationships between microstructural changes versus hardness across the entire hardened layer and microhardness in the very thin surface layer, the latter were measured by the Vickers method. Thus, Figs. 10 and 11 show the hardness profiles versus the induction-hardened layer depth according to Vickers at the load of 20 N or measurements of microhardness according to Vickers in a very thin surface layer to a depth of 150 μm at the load of 1 N.

The hardness of the surface layer after induction surface hardening is very uniform in all the investigated main bearing locations and amounts to around 520–550 $HV_{2.0}$. The hardness profile highly conforms to the residual stress profile, which is confirmed by the drop in hardness in the transition zone. The hardness profile in the transition area is likewise very steep and points to high stress concentrations on this location when the crankshaft is in the loaded state.

Fig. 10 presents the hardness profile in an induction surface hardened layer to a depth of 5.0 mm and the microhardness profile to a depth of 150 μm on the bearing location A. From the hardness measurements we can see that the quenched and tempered steel has a hardness around 220–260 $HV_{2.0}$ and the surface hardened layer has a hardness around 540 $HV_{2.0}$. In the surface hardened layer we can also note a slight increase in hardness as a function depth, which is conditioned by microstructural differences due to varied cooling rates of the surface layer. The surface is cooled under the effects imposed by the cooling medium, yet at a greater depth the effects of the medium are accompanied by a more expressed effect of the cold mass of the core, resulting in the formation of very fine martensite and greater hardness in greater depth. In Fig. 11, we can see the hardness profile in the hardened layer and the microhardness profile in a very thin surface layer for the bearing location C.

3.7. Analysis of residual stresses after induction surface hardening and grinding

The last phase in the manufacturing of crankshafts is fine grinding where in order to achieve the desirable condition of the surface and the surface layer, i.e. we have to ensure:

- suitable dimensions of the particular bearing locations with respect to the allowable deviations;
- suitable surface roughness;
- that the grinding stresses are compressive or lowest tensile so that the favourable stress profile obtained by induction surface hardening of the surface layer is maintained;
- smallest changes possible in the microstructure and thus also smallest changes in the hardness and microhardness profiles in the heat-affected zone after grinding.

How is it possible to assure a desirable surface and surface layer quality after induction surface hardening and fine grinding? Finding an answer to this question requires a very good knowledge of the process of grinding on the micro-level as well as knowledge of mechanical and heat effects acting on the layer of the workpiece including the type and

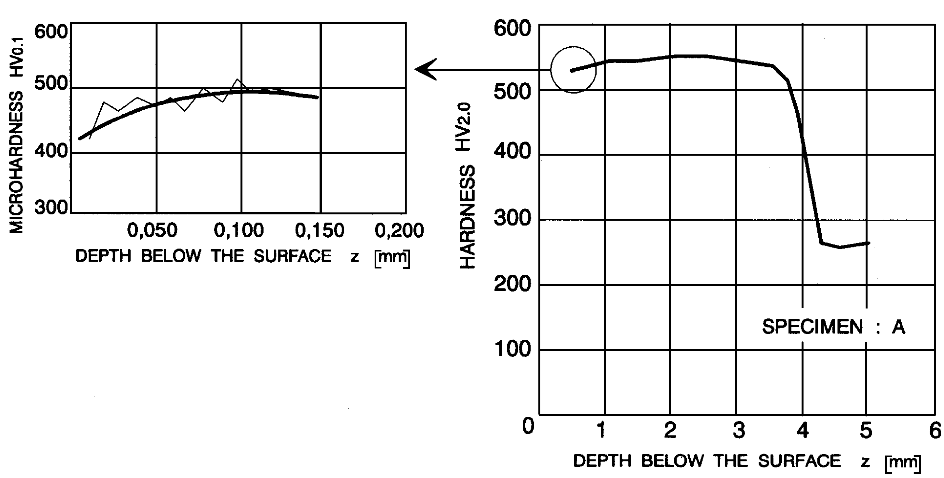

Fig. 10. Hardness profile in the induction surface hardened layer and microhardness profile in a very thin surface layer for the bearing location A.

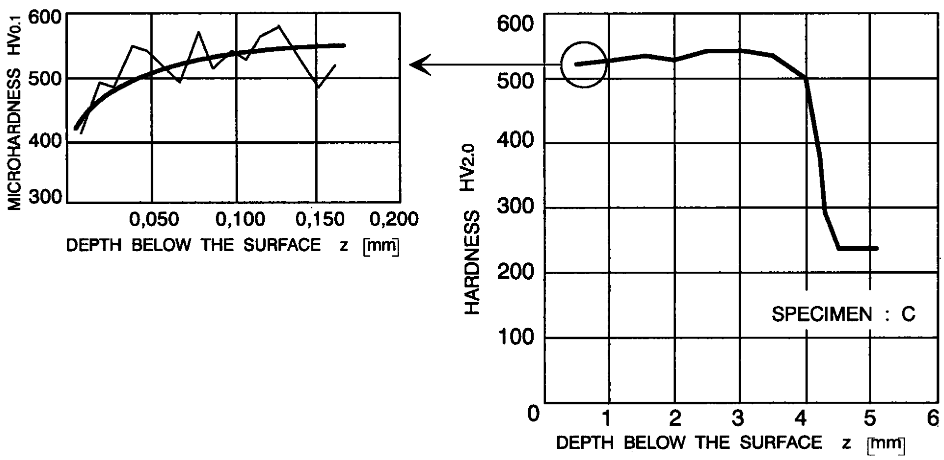

Fig. 11. Hardness profile in the induction surface hardened layer and microhardness profile in a very thin surface layer for the bearing location C.

condition of the grinding wheel. An all-inclusive consideration of the numerous influences of the kind and condition of the tool on the changes on the surface and in the surface layer of the workpiece in the given machining conditions is described by the term "surface integrity" [23].

For the grinding process the following conditions have been selected:

- different kinds of grinding;
- different grinding conditions (gentle, conventional, abusive).

Because of thermomechanical loads in the thin surface layer during the grinding process, on the micro-level very complex physical and chemical processes are going on. For an accurate description of the conditions in the contact zone in machining a given material it is necessary apart from the grinding method, to consider also the kind of material from which the grinding wheel is made, its structure and grinding conditions. The heat conditions in grinding are a result of the conditions in the contact between the individual grinding grains and the workpiece material and deformation energy in chip formation in the shear zone. The amount of generated heat is strongly dependent on the chosen machining conditions and is conducted mainly through the chip while a smaller part of the generated heat is transferred through heat transfer into the thin surface layer of the workpiece. Heating of the chip does not cause any particular difficulties, but the heating of the thin surface layer of the workpiece creates the conditions for different mechanical and thermokinetic processes which cause microchemical changes. The heating up of the thin surface layer of the workpiece can leave certain undesirable effects which change the properties of the product's surface layer and thus harm its operational abilities. The generated friction heat is transferred through heat transfer phenomenon from the contact between the grinding grain and the workpiece into the grinding grain. The increased amount of heat on the grinding grain or grinding wheel intensifies the wear processes and damage of particular grinding grains which follow very different and complex mechanisms and in the final phase affect the serviceability and operational life of the tool.

The grinding tool consists of grinding grains representing each by itself a single-cutting tool of rather different, random shape and orientation towards the workpiece surface during the grinding process. Grinding grains are interconnected with an appropriate binder which is defined by different degrees of porosity of the grinding wheel structure. Therefore, it is necessary to know also the force necessary for the breaking of grinding grain from a given structure expressed by the grinding wheel hardness. Simultaneous changes in volume proportions of the grinding grains and binder can create different structures of the grinding wheel which do not behave in the same way. This means that by changing the kind of material for the grinding wheel and the binder it is possible to achieve equal effects also by changing the structure of the grinding wheel. From this follows that by a suitable combination of the influential parameters it is possible to achieve a longer life and wear resistance of the wheel in equal kinematic conditions of the wheel and the workpiece. The wear of the grinding grains is a result of mechanical and thermal effects which are reflected in reduced cuttability. Fig. 12 shows the basic forms of wear and damage on the grinding wheel grains expressed by characteristic changes on the grinding grains. Due to mechanical loads on particular grinding grains, in the contact or on the friction surfaces with the workpiece short-lived but intensive heat effects are created. In this cases, blunting of the grinding grains (Fig. 12A), breaking off of the grinding grains (Fig. 12B) or splitting of the grinding grains (Fig. 12C) may happen. Requirements are quite often set that a worn out grain should fall from the grinding wheel at a certain moment. A worn out grain has the contact surface typically increased, which causes that during the cutting process the forces on the grinding grain are higher than the binding forces between the grains, therefore the grains fall

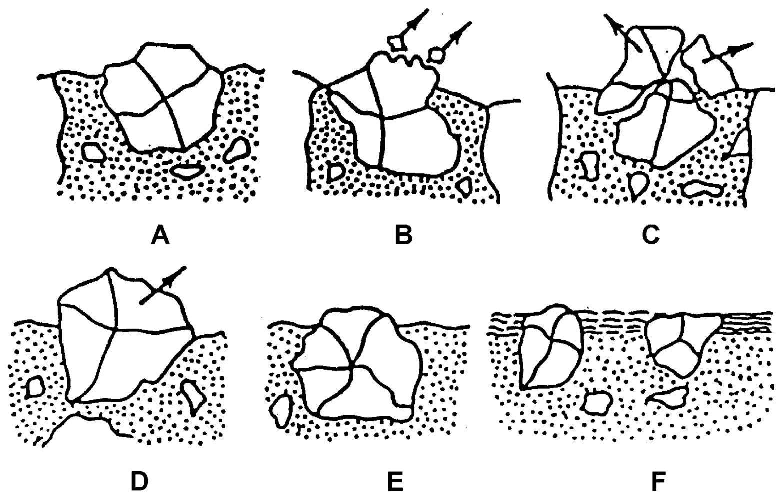

Fig. 12. Basic forms of wear and damage on the grinding wheel grain.

out (Fig. 12D). It is expected that the manufacturing engineer will carefully choose all the parameters of the process so that the worn-down grains fall out. This ensures a more efficient machining and reduced thermomechanical effects in the thin surface layer of the workpiece material. For creating a suitable quality of the surface and surface layer of the workpiece it is necessary to ensure that grinding grains would fall out, and that the activation of new sharp grinding grains is made possible. Here it is very important to choose such cutting condition that would make the grains fall out only when their cuttability is reduced. Fig. 12E illustrates characteristic blunting of the grinding grain due to chemical reactions at high temperatures. Chemical reactions at high temperatures are frequently followed by filling the pores with overheated, highly plastic chips of the workpiece material (Fig. 12F). In cases when the pores on the wheel surface get filled, the temperature in the contact zone rises and changes the progress of the temperature cycle into the depth of the workpiece. The maximum temperature of the temperature cycle on the surface rises and so does the temperature in the particular depths of the workpiece material. This results in greater depth of the heat affected zone in the material, which may have serious consequences in terms of surface layer properties of the workpiece material. Generally, we can state that the blunting of the grinding grains makes the contact surfaces between the grains and the workpiece larger, which creates the conditions for increased mechanical effects in the contact zone and higher heat input accompanied by stronger heat effects in the surface layer of the workpiece.

A plastically deformed layer is created because of interaction between the grinding tool and the workpiece on the place where the chip separates from the base. A result of this is the hardening of the thin surface layer of the workpiece material and occurrence of internal stresses which may lead to failure of the thin surface layer and/or deformation of the workpiece/product with the presence of residual stresses at the end of machining. Macro- and micro-analysis with optical and/or electronic microscopes shows microcracks and/or other damage on the surface caused by inadequate grinding method or procedure. Microscopic assessment of the surface state and damage on the surface quite often point back to inadequate grinding conditions. The most frequent surface damage includes hollows, mars, torn-off areas, built-up edges of the workpiece or the tool, etc. It is often necessary to consider also the generated heat effects which cause microstuctural and/or chemical changes accompanied by dimensional changes. The damage on the workpiece surface should be taken very seriously since in the operation with another element in the mating pair this may give rise to very detrimental friction conditions.

The engineer should be aware that surface integrity depends on the tribological conditions in the operation of a component/assembly. Therefore, adequate knowledge for the assessment of tribological conditions of a component in operation is very important for the prescription of machining that would result in the wanted surface condition and subsurface layer. In general, we can state that there are two tribological systems: the first is the one present during the machining, and the second is acting in operation. In both tribological systems, however, it is the properties of the workpiece material and its condition prior and after machining that play a key role.

Fig. 13 presents the temperature cycles on the specimen surface as a function of depth in the hardened steel at given grinding conditions. The temperature cycles can be treated separately as heating phase and then also as cooling phase. In the analysis of microstructural changes in a thin surface layer of the hardened steel specimen it is possible to determine the size of the remelted and re-hardened layer. In Fig. 14, we can see the time variation of the maximum temperature on the surface at the particular depths according to grinding temperature cycles with respect to the work speed V_w. Knowing the temperature of melting and the

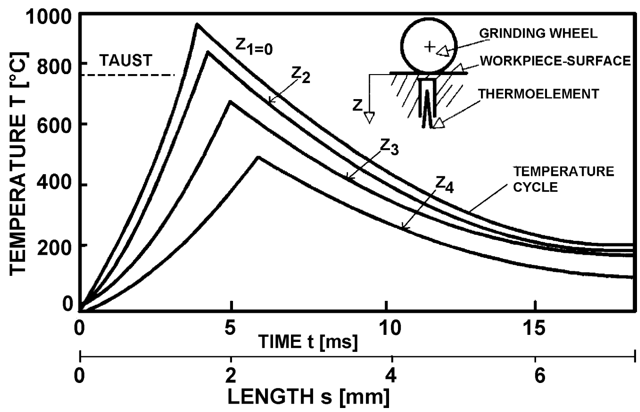

Fig. 13. Grinding temperature cycles in different depths in the hardened steel at given grinding conditions.

temperature of austenitisation of discussed steel, we can define the depth of the remelted layer and the depth of the re-hardened layer.

Under different machining conditions of grinding, different temperature cycles were obtained on the surface and in the depth of the heat-affected zone which has effected microstructural changes and changes in the microhardness and residual stresses. What kind of microstructural changes will occur in the surface layer of the specimen depends on the temperature in the contact zone between the grinding wheel and the specimen and the variation of temperature through the specimen depth, respectively.

In the grinding process, the changes of temperature in the thin surface layer of the specimen are very important. Temperature measurements provide data on temperature cycles, which, because of the relative movement of the specimen and the grinding wheel, indicate the variation of temperature both in heating and cooling of the given spot at the specimen. The maximum temperatures achieved at the surface and in the surface layer, respectively, are also very

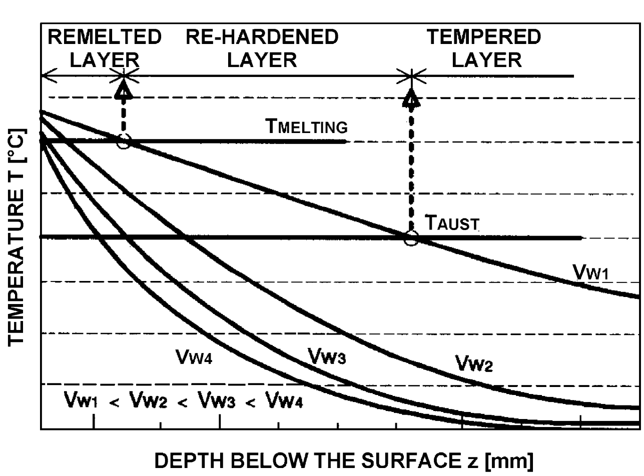

Fig. 14. Maximum temperature drop as a function of depth in the hardened steel at various work speed V_w.

important. A distinction can be made between three characteristic cases of temperature cycles, which is to say:

- The maximum temperatures at the surface and in the surface layer, respectively, are higher than the melting temperature of the specimen material depending on the temperature cycles. Such conditions may occur due to very sharp grinding conditions or due to the selection of an inappropriate grinding wheel with regard to the specimen material. The depth of the remelted layer is only a few micrometers and makes a very fine ledeburite microstructure containing fine cementite spread in residual austenite. The newly formed microstructure has a slightly lower hardness than martensite. The residual stresses in the thin surface layer will be tensile due to plastic deformation of the surface layer in grinding caused by tensile forces in the contact zone of the specimen material and to this should be added also the tensile stresses induced by the occurrence of residual austenite.
- The maximum temperature in the contact zone is lower than the temperature required for the beginning of melting of the given material and higher than the austenitising temperature. The lower temperature, that is the austenitising temperature, will shift because of a high rate of heating of the specimen towards higher temperatures as known from transformation diagrams. Provided the previous microstructure of the surface layer was martensite–cementite–carbide, after grinding a finer martensite microstructure with a higher carbon content obtained at the expense of cementite–carbide phases and with a possibility of a lower a content of the residual austenite may be expected in the thin surface layer. The modified content of the cementite–carbide phase depends on the heating conditions, whereas the content of the residual austenite depends on the cooling conditions.
- The maximum temperature in the contact zone is lower than the temperature required for the beginning of austenitisation and higher than the lower temperature which is limited by the temperature of steel tempering and amounts to approximately 200°C. In this case the grinding conditions are very mild so that with the selection of the right kind of grinding wheel neither major no important changes are expected either or in the surface layer. In the surface layer only martensite tempering may occur if it was not performed already during the induction surface hardening of the specimen.

In conventional grinding conditions, on bearing location A relative grinding tensile stress amount to +425 N/mm^2 and then change the sign in the depth around 175 μm, as shown in Fig. 15. The relative grinding stress is obtained by measuring the residual stress after induction surface hardening and then by measuring on the same spot after induction-hardening and grinding and then calculating their difference. In Fig. 16, we can see the measured absolute residual stress profile after induction surface hardening and

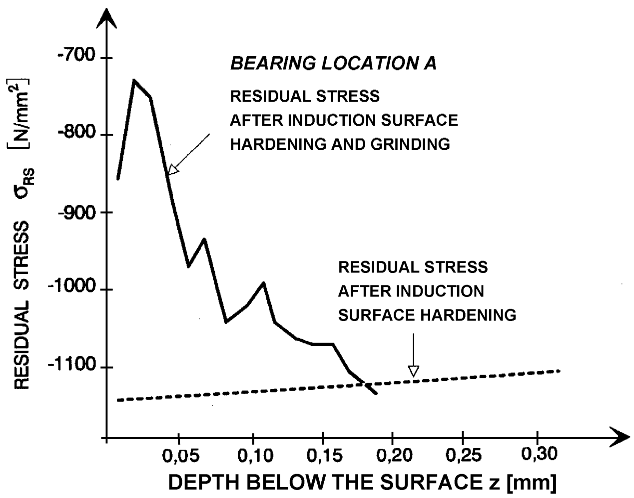

Fig. 15. Residual stress profile below the surface after induction surface hardening and residual stress profile after induction surface hardening and grinding on bearing location A.

grinding, and the measured residual stress profile after induction surface hardening. Fig. 16 shows the absolute residual stress profile after hardening and grinding on bearing location A as well as the average residual stress after induction surface hardening, and then the relative grinding stress can be calculated. The results confirm as predominant the residual stresses, stresses induced by the plastic deformation of the material and a lesser influence of tensile stresses caused by the formation of residual austenite. On the basis of the measurements of residual stresses after induction surface hardening and/or induction surface hardening and grinding, we can conclude that:

- Special attention should be paid to the selection of the kind of the grinding wheel in terms of grinding wheel material, binding agent, hardness and pore density, since by a right selection we can contribute to higher cutting efficiency concerning the plastic deformation of the workpiece material. In this way we can keep the grinding tensile stresses as low as possible and make the compressive residual stresses induced by induction surface hardening the prevailing kind.
- For residual stresses after induction surface hardening and grinding, the conditions of gentle grinding are a more favourable choice. They lower to a lesser extent the desirable compressive residual stresses after induction surface hardening.
- Grinding conditions can be chosen also so that the melting temperature of the specimen material is not exceeded (gentle or conventional grinding conditions). Then the favourable compressive stresses after induction surface hardening are lowered only due to plastic deformation of the workpiece material during the process and thus relatively low tensile residual stresses are thus obtained. However, we should take into account that this will significantly lower the productivity.
- Abusive grinding conditions contribute to blunting of abrasive grains, which produces a larger contact zone between the abrasive grains and the specimen surface, which in turn produces a stronger overheating of the thin surface layer. In such cases burns will occur that specimen surface and consequently, softened spot which do not ensure the working life required of a machine component.

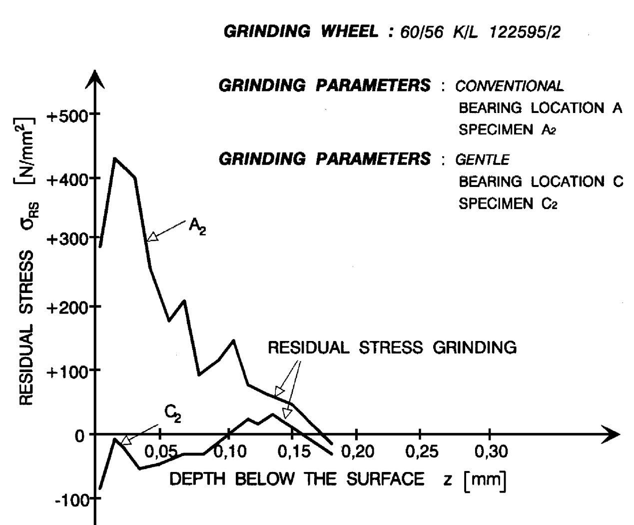

Fig. 16. Grinding residual stress profiles below the thin surface layer on bearing locations A and C at various grinding conditions.

Induction surface hardening creates very desirable residual stress state. Residual stresses are always of compressive nature and are usually present to the depth of the induction surface hardened layer. A major difficulty in induction surface hardening is, however, to ensure a very slight/slow variation in microhardness and the existence of compressive residual stresses in transition areas to the microhardness of the core material. By gently grinding varying the hardness and existence of compressive stresses in the transition area it is possible to diminish the notch effect induced by stress concentration. Additional grinding of induction surface hardened deteriorates the stress state in the surface layer, since grinding has always induced tensile stresses. By a right selection of machining conditions and grinding wheel taking into account its properties, the engineer will contribute to lesser tensile residual stresses and will avoid deteriorating the favourable residual stress state after induction surface hardening.

4. Conclusions

Induction surface hardening of machine parts and especially crankshafts is a very complex process involving a whole range of possible heat treatment methods, which are all reflected in either good or bad serviceability. The heat treatment engineer has to be aware of the different effects of particular design shapes of induction coils, be familiar with electromagnetic phenomena and eddy currents, and have some experience in the right choice of energy inputs necessary for heating. The energy needed for heating can be provided by changing the generator power as well as changing the frequency of the current. In progressive hardening, to achieve a suitable energy input, the workpiece feed rate or the rate at which the coil is moved have to be adjusted, whereas in single-shot hardening suitable energy input is achieved by adjusting the heating up time with a high frequency current. An essential advantage of induction surface hardening is that it is possible to achieve a sufficient repeatability of the hardened layer thickness on the workpiece as well as a desirable or even prescribed hardened layer profile, ensuring sufficient hardness and favourable distribution of residual stresses in the hardened layer. A variety of steels and a whole range of induction hardening methods provide the possibilities for very accurate planning of the size and distribution of residual stresses. This is of growing importance since manufacturers are more and more often required to produce machine components, which among other surface properties, will have to have quite specific residual stress distribution along the depth of the hardened layer. It has become a proven fact that high compressive stresses ensure high fatigue strength of machine components and reduce the danger of the occurrence and growth of cracks on the surface of components. As far as induction surface hardening is concerned, it is also quite important to choose the right quenching medium and method of quenching. For this reason, engineers have to direct their attention not only to the method of heating and possible overheating of the surface layer but also to the methods of quenching and the right choice of the medium for quenching.

References

[1] P.A. Hassell, N.V. Ross, Induction Heat Treating of Steel, ASM Handbook™, Vol. 4, Heat Treating, 1991, pp. 164–202.

[2] V.I. Rudnev, R.L. Cook, D.L. Loveless, M.R. Black, Introduction to heat treatment, basic principles, computation, coil construction and design considerations, in: G.E. Totten, M.A.H. Howes (Eds.), Steel Heat Treatment Handbook, Marcel Dekker, New York, pp. 1997, 765–767 (Chapter 11A).

[3] V.I. Rudnev, R.L. Cook, D.L. Loveless, M.R. Black, Introduction to heat treatment, modern power supplies, load matching, process control, and monitoring, in: G.E. Totten, M.A.H. Howes (Eds.), Steel Heat Treatment Handbook, Marcel Dekker, New York, 1997, 873–874 (Chapter 11B).

[4] M.G. Lozinski, Industrial Applications of Induction Heating, Pergamon Press, Oxford, 1969.

[5] Electromagnetic Induction and Electric Conduction in Industry, Heat Treatments by Induction, Preface by Jean Lucas, Centre Francais de I'Electricete, 1997, pp. 419–468 (Chapter 9).

[6] P.K. Braisch, The influence of tempering and surface conditions on the fatigue behaviour of surface induction hardened parts, Mater. Sci. Forum 102–104 (1992) 319–334.

[7] M. Melander, Computer calculation of residual stresses due to induction hardening, in: E. Macherauch, V. Hauk (Eds.), Eigenspannungen: Entstehung–Messung–Bewertung, Band 1, Deutsche Gesselschaft für Metallkunde, Oberursel, 1983, pp. 309–328.

[8] S. Denis, M. Zandona, A. Mey, M. Bonfoussi, A. Simon, Calculation of internal stresses during surface heat treatment of steels, in: V. Hauk, H.P. Hougardy, E. Macherauch, H.D. Tietz (Eds.), Residual Stresses, Deutsche Gesselschaft für Metallkunde, Oberursel, 1993, pp. 1011–1020.

[9] B. Raniecki, A. Bokota, S. Iskierka, R. Parkitny, Problem of determination of transient and residual stresses in a cylinder under progressive induction hardening, in: G.E. Totten, B. Liščić, H.M. Tensi (Eds.), Proceedings of the Third International Conference on Quenching and Control of Distortion, American Society of Metals, Prague, Czech Republic, March 1999, pp. 473–480.

[10] T. Inoue, H. Inoue, F. Ikuta, F. Horino, Simulation of dual frequency induction hardening process of a gear wheel, in: G.E. Totten, B. Liščić, H.M. Tensi (Eds.), Proceedings of the Third International Conference on Quenching and Control of Distortion, American Society of Metals, Prague, Czech Republic, March 1999, pp. 243–250.

[11] O. Longeot, C. Delalean, Simulation numérique des procédés de traitement par induction, Traitement Thermique 280 (1995) 33–47.

[12] E. Vatev, Influence de la méthode et de la profondeur de trempe par induction sur la répartition des contraintes résiduelles sur la section transversale, Traitement Thermique 89 (1974) 43–54.

[13] J. Grum, D. Ferlan, Residual internal stresses after induction hardening and grinding, in: D.L. Milan, D.A. Poteet Jr., G.D. Pfaffmann, V. Rudnev, A. Muehlbauer, W.A. Albert (Eds.), Proceedings of the 17th ASM Heat Treating Society Conference, Including the First International Induction Heat Treating Symposium, American Society of Metals, Metals Park, OH, 1998, pp. 629–639.

[14] Ch. Lai, Quality control of induction hardened cast iron cylinder head valve seats, Mater. Sci. Forum 163–165 (1994) 367–374.

[15] G.D. Pfaffmann, Innovations in induction heat treating techniques for control of distortion and improving dimensional results, in: D.L. Milan, D.A. Poteet Jr., G.D. Pfaffmann, V. Rudnev, A. Muehlbauer, W.A. Albert (Eds.), Proceedings of the 17th ASM Heat Treating Society Conference, Including the First International Induction Heat Treating Symposium, American Society of Metals, Metals Park, OH, 1998, pp. 677–686.

[16] M. Moris, R. Snoeys, Heat affected zone in grinding operations, in: F. Koenigsberger, S.A. Tobias (Eds.), Proceedings of the 14th International Machine Tool Design and Research Conference, Manchester, 1973, pp. 569–669.

[17] W.J. Tomlinson, L.A. Blunt, S. Spraggett, White layers on surface of ground EN24 steel: 1 microstructure composition, internal stress and corrosion properties, Surf. Eng. 5 (3) (1989) 229–234.

[18] W.J. Tomlinson, L.A. Blunt, S. Spraggett, White layers on surface of ground EN 24 steel: 2 effect of grinding conditions on formation and surface metallography, Surf. Eng. 6 (2) (1990) 129–132.

[19] Brinksmeier, A model for the development of residual stresses in grinding, in: A. Niku-Lari (Eds.), Advanced in Surface Treatments: Technology, Applications, Effects, Vol. 5, IITT/Pergamon Press, Oxford, 1987, pp. 173–189.

[20] E.D. Walker, Soma aspects of residual stress in parts heat treated by the induction method, in: L.J. Vande Walle (Ed.), Residual Stress for Designers and Metallurgists, Materials/Metalworking Technology Series, American Society of Metals, Metals Park, OH, 1980, pp. 41–50.

[21] M. Mahdi, L. Zhand, Applied mechanics in grinding. Part 7: Residual stresses induced by the full coupling of mechanical deformation, thermal deformation and phase transformation, Int. J. Mach. Tools Manuf. 39 (1999) 1285–1298.

[22] K.E. Thelning, Steel and its heat treating, in: Induction Hardening, Bofors Handbook, Butterworths, London, 1975, 432–451 (Chapter 6.6).

[23] M. Field, J.F. Kahles, J.T. Cammet, Review of measuring method for surface integrity, Ann. CIRP 21 (2) (1971) 219–237.