Residual Stresses — Measurement and Causes in Machining Processes

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Summary

The functional behaviour of a machined component is substantially determined by the physical state of its surface including the residual stress distribution near the surface. Recently, it became clear that more exact methods of layout for machined components compel one to take "surface integrity" as defined by M. Field /1/ and herewith residual stresses into consideration. Residual stresses directly influence the deformation of workpieces, their static and dynamic strength, and their chemical and electrical properties.

According to the relevance of residual stresses generated by machining, several laboratories affiliated with CIRP worked on a cooperative investigation of measurement techniques to define the state of the art. Measurements of residual stress distributions generated by some important machining processes have been made. This paper gives a report and tries to show how the possible sources for development of residual stresses are involved.

1. Detrimental and Favourable Influences of Residual Stresses

Residual stresses in a workpiece are a function of its material, its forming and machining history. Residual stress can enhance or impair the functional behaviour of a machined part. Economic and technical aspects require better utilization and higher loading of machines and plants and their components. Thus methods of projection and design have to be improved /1/. The physical state of high-duty workpieces has to be described precisely. This includes the knowledge of residual stresses in the component and especially in its surface layers.

The machining processes which generate the functionally relevant surfaces of a component have great importance for the development of the physical state of the surface and the residual stress distribution in it. For many applications, the properties of a part's surface are dominant for the functional behaviour of the whole component. Fig. 1 gives a summary of the most important effects of residual stresses on mechanical and electrical components. This list is not complete. There are other effects such as optical, acoustical or thermal results of residual stresses which cannot be discussed here. Some examples of the effects mentioned in figure 1 are described in following sections.

1.1 Deformations by Residual Stresses

Residual stresses act on a body without external forces or moments. The internal forces form a system of equilibrium. If parts of the body are taken away, for instance by machining, the state of equilibrium is generally disturbed, and the body has to react by deformations. This is an effect well-known to production engineers which can be observed, for example, when machining a casting. If this casting is not heat treated for stress relief and if it is unsymmetrically machined, deformations can occur after roughing and taking off large portions of the stressed material before finishing. The deformation of the part is roughly proportional to the removed cross-section of material. In the subsequent finishing only thin layers are removed so that the detrimental effects of the residual stresses from the casting process are minimized.

This effect must not be mixed up with the input of residual stresses by machining (fig. 2). As will later be explained in detail, the machining process generates residual stresses by plastic deformation or metallurgical transformations. These residual stresses have only limited depth of penetration on the order of some hundredth of millimeters. But especially for thin workpieces, this can also lead to relevant deformations. By ploughing of a long beam with a thickness of 20 mm, the deflection may be about 1 mm /2/. During the machining process or shortly afterwards, thermal influences can cause further deformations. During machining the workpiece can be heated asymmetrically. By this temperature profile and the thermal expansion thermal stresses are generated and result in an additional deformation which, however, diminishes after temperature compensation (fig. 2).

An important role is played by deformations caused by residual stresses in sheet metal forming /3,4,5,6/. Generally, plastic and elastic strains arise by bending. The bending angle given by the form of the die or the position of the tools is not identical with the angle at the workpiece after force release. Because of the elastic strains the bent part springs back (fig. 3). The spring-back angle is especially large at locations of high elastic strains as compared with the plastically formed part of the sheet. A correction of the tools by this deviation is necessary /7,8/. Similar effects have to be considered where nonuniform — especially elastic-plastic deformations as in twisting — take place /9/.

1.2 Influence on Static Strength

From a macroscopic point of view residual stresses act like a prestress on materials which are deformable and which have a characteristic yield point. The residual stresses must influence the level of the yield strength. Assuming a criterion of plastic flow, the elastic limit can be calculated if the stress distribution is given. This was experimentally proved by several authors /10,11/. Specimens of free cutting steel 9232 Pb were provided with different residual stress distributions by drawing and dressing. In fig. 4 the elastic limit
showed to depend on the maximum residual stress component in the axial direction. It can be seen, that the elastic limit \( (R_p = 0.005) \) is decreased up to 40\% from the unstressed state. The beginning of plastic deformation during the tensile test is eased by residual stresses considerably which follows from the prestressed-material-model. In pure tension or compression loading, the elastic limit must be lowered by the presence of uniaxial residual stresses independent of their distribution. In bending or multiaxial stress distributions even an increase of the elastic limit can be realized.

Increasing the strength of a component by prestressing is extensively used in technical applications. Dies for extrusion are often built by two cylinders to be able to prestress the inner part and to bring it to a less critical state during operation. In high-pressure-physics this principle is still extended. Fig. 6 shows a "belt" apparatus which is used to synthesize diamonds /14/. The synthesis is accomplished at temperatures of more than 1600 K at pressures of more than 55 kbar.
formations. They have the shape of a truncated cone and are loaded along the axis of the cone. They are designed to be elastically deformed 1/4 of the geometrically possible stroke. The acting stresses thereby exceed the yield strength, which means that the spring tends to relax /7,16/. This can be avoided by imposing a residual stress state (fig. 8). The figure shows the theoretical stresses by external force and the stress distribution which results from these and the residual stresses. The latter can be generated by overloading the disk springs in a special program. It has been experimentally proved by residual stress measurements /19/ that, after this treatment, practically no relaxation or change of stress distribution takes place.

In the preceding examples the loaded components consisted of plastically deformable material. If the material is brittle, residual stresses may lead to cracks if the resulting stresses exceed the strength of the material at any point. Fig. 9 shows the spindle of a grinding machine which was nitrided and then ground. Using the magnetic flux test axial parallel cracks can be made visible. A cross-sectioning and metallographic preparation explains the cause of these cracks. Near the surface a dark nitrided layer with a depth of \( H = 0.4 \) mm can be seen. By the nitriding itself high tangential stresses cannot be developed, because thermal or transformation influences are of minor importance. Therefore the cracks must result from the grinding process after nitriding. Thermally induced tangential stresses are generated during circumferential grinding at high metal-removal rates. Being nitrided, the material cannot deform plastically; therefore, it cracks.

Fig. 10 shows the crankshaft of an eight-cylinder four-stroke Diesel motor for a locomotive. The journal of 89.5 mm diameter has two cracks in 45° direction to the axis /20/. When the part was tested after heat treatment, it was undamaged. After grinding and loading of the component these typical cracks occurred. A subsequent test showed soft layers beneath the surface. They were generated by the faulty grinding process in connection with high residual stresses which lead to the cracks.

1.3 Influences on Dynamic Strength

The influence of residual stresses on fatigue strength was stated long ago /21,22,23/ and has been proved since in numerous investigations. Extensive tests have been made by M. Field and coworkers /24/. Fig. 11 gives a characteristic correlation between residual stresses induced in a specimen by grinding under various conditions and the fatigue strength /24/. The surface grinding process was varied from \( v_g = 10 \) m/s to \( v_g = 30 \) m/s. The wheel hardnesses were H, F and N, the coolant was air, oil, or emulsion, and the dressing, coarse and fine. The resultant maximum residual stresses varied from \(-80 \) N/mm² to \(1000 \) N/mm². Over this wide field of conditions a very good correlation of fatigue strength and maximum residual stress could be stated for the steel AISI 4340.

In fig. 12 the influence of high and low stress can also be found. Here microscopic data of the surface are given too. It can be seen, that higher roughness decreases the fatigue strength as was expected but the influence even for longitudinal or traverse grinding direction is much less than that of the physical state of the surface.

As far as the decrease of fatigue strength with ten-

Fig. 10: Grinding cracks in a crankshaft (Pohl)

Fig. 11: Fatigue strength and residual stresses (Field/Koster)

Fig. 12: Fatigue strength versus residual stress and roughness (Field)

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silic stresses in concerned, Syren [25] obtained a similar result for hardened carbon steel Cr 45. Yet he stated that a heat treatment also had strong influence. The dependency was much less or could not be found for mild steel [26].

The fatigue fracture of the tested parts started at the weakest point. Thus, not the average value of the stress but the local extreme is relevant. This is especially important for those machining processes which generate scattering stress distributions. For example, Field and Prevey found strong variations in grinding process with aluminum oxide wheels [27].

The effect of residual stresses and faulty grinding operations can be seen from gear tests [28,29]. Gears of casehardened steel 16 Mn Cr 5 were ground on a teeth grinder using normal conditions and conditions which lead to burning (fig. 13). Although no cracks were generated, the durable flank pressure was decreased by 25 %.

The same investigation showed that with these unfavourable grinding conditions the residual stresses in the surface of the tooth flank in the axial and radial direction were highly tensile. (Kosche)

1.4 Chemical Resistance

If certain metals are subjected to stresses and are exposed to a corrosive environment over a period of time, stress corrosion can be observed. The conditions under which this effect arises are a specific sensitivity of the material, the existence of tensile stresses in the surface and the presence of a corrosive medium. Fig. 14 shows the surface of austenitic chromium-nickel steel after tension in a solution of sulfuric acid and sodium chloride. The cracks are due to stress corrosion. There are different theories about the dominant process during stress corrosion. The electrochemical hypothesis assumes potential differences between the precipitations at the grain boundaries or in the grains and the adjacent matrix so that the precipitates are dissolved anodically. Tensile stresses open cracks developed in this way. They rupture the surface film in the crack root and bring pure metal to the corrosive environment. Stress corrosion is one of the main causes of failures in chemical plants (fig. 15) [30]. During a period of one year, 60 % of the occurring failures in a large chemical company were caused by corrosion. More than 20 % of the

corrosion failures

Fig. 15: Failure statistics of metal structures in a chemical plant (Gramberg/Horn)

corrosion failures

1.5 Magnetization

The magnetic properties of a ferromagnetic body depend on its physical state. In many applications these dependencies are used for measuring and testing purposes. For instance, as a disturbance of the magnetic flux in a material. Therefore the flux distribution or the flux intensity can be used to detect such faults in the surface or inside the body. Magnetization effects can also be used to investigate changes in the crystallographic structure of a ferromagnetic material. The coercive force, for instance, is very sensitive to hardening effects and can be used for in-process-measurements during machining operations.

The magnetic properties are directly influenced by residual stresses and local disturbances of the crystallographic structure. Fig. 16 shows the texture of a soft magnetic nickel alloy and its application in a magnetic head of a machine [31]. The information density on the tape is determined by the focusability of the head. This is dependent on the width of the un-

Fig. 16: Magnetic head textures of the nickel alloy (ref.: Spur/Dean)

disturbed zone including the air gap between the two poles. The surfaces on the poles have to be machined by lapping. In fig. 16 the deformed grains of these surfaces after electropolishing a thin layer of 13 µm and after removing 50 µm can be seen. The upper layer shows distinctive contrasts inside the grains. These are due to local dislocations (local tilts of the lattice) [31]. The soft magnetic properties of the material and thereby the focussability of the head are degraded by these mechanical influences.

2. The Nature of Stresses and Residual Stresses

In fig. 17 a body is subjected to external forces $L_1$, $L_2$, ..., $L_6$. To describe the internal state of the structural material, the cross-sectional principle is used. It is assumed that the body is divided into two parts. By this dissection internal forces are set free, which are continuously distributed over the cross section. Considering one of the two parts, the forces on the cross section have to be applied to keep it in the

Fig. 17: The cross-sectional principle
The superposition principle can be used only if there are strains in lateral directions as where \( E \) is the Young's modulus for uniaxial stress.

The external forces cause deformations of the body without external forces or moments on its surface (surface forces) and without volume forces. These residual stresses exist only when the strain tensor cannot be derived from a steady displacement vector. The residual strain which is not compatible with the displacement vector is called the stress source \( \varepsilon_0, \varepsilon_1, \ldots \), \( \gamma_{yz}, \gamma_{xy} \). Now Hooke's law can be written

\[
\varepsilon_x = \frac{E}{1 - \nu} \sigma_x + \frac{\nu}{1 - 2\nu} \left( \sigma_y + \sigma_z \right)
\]

where \( \varepsilon \) and \( \gamma \) are the strains to which a body is subjected from a stress free state. As long as plastic deformations are avoided the stress sources and the deformations by stresses can be superimposed. The state of residual stresses can be considered to be caused by the action of residual strains \( \varepsilon_0, \varepsilon_1, \ldots \) and elastic deformations in a continuum originally free of stresses; or in terms of stresses

\[
\sigma = \sigma_0 + \sigma
\]

Here \( \sigma \) are the residual stresses, \( \sigma_0 \) are the stresses which can be formally calculated from the stress sources \( \varepsilon_0 \) by applying Hooke's law and \( \sigma \) are stresses derived from the deformations \( \varepsilon \).

Reiner defined two problems of the residual stress mechanics: first, the initial deformations \( \varepsilon_0 \) are given and the caused residual stresses are sought; second, the residual stresses are given by experimental analysis and the stress sources \( \varepsilon_0 \) are sought.

The first problem is generally solvable. The procedure can be shown by an example. A flat prismatic body is machined on one side (fig. 18). By this process a layer of a thickness of \( \delta \) is plastically deformed so that its length is uniformly shortened.

Knowledge of stresses and strains caused by external forces and moments is essential to judge the load of the material and the displacements of a structural part. But these data are not sufficient. The residual stresses have to be considered too, as has been shown before.

Residual stresses are those stresses which exist in a body without external forces or moments on its surface (surface forces) and without volume forces. These residual stresses exist only when the strain tensor cannot be derived from a steady displacement vector. The residual strain which is not compatible with the displacement vector is called the stress source \( \varepsilon_0, \varepsilon_1, \ldots \), \( \gamma_{yz}, \gamma_{xy} \). Now Hooke's law can be written

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The first problem is generally solvable. The procedure can be shown by an example. A flat prismatic body is machined on one side (fig. 18). By this process a layer of a thickness of \( \delta \) is plastically deformed so that its length is uniformly shortened.
The second problem - the determination of stress sources from measured residual stresses - cannot be solved without further information, although it seems to be simply the inverse of the first problem. It can easily be seen, however, from the solution of the first problem, that any initial deformation $\epsilon$ can be added to the given state $\sigma$ without affecting the residual stress distribution, if these additional deformations can be derived from a compatible displacement vector. This is, for instance, a constant deformation over the whole cross section from $z = 0$ to $z = w$.

In machining processes and by heat treatment the stress sources can be generated by mechanical, thermal and transformation means (Fig. 19). If a cylindrical specimen is heated below the $A_\text{c1}$ level and then quenched, the stress distribution is axisymmetric. The stress distributions can also be generated by mechanical treatment. After the whole body has reached low temperature the outside domain contains compressive stresses, while the inside contains tensile stresses.

Fig. 19: Typical residual stress distributions

shear stresses $\tau_{xz}$ are negligible. The axial and tangential stresses in the surface which changes to the inner part. If a hollow cylinder is treated in the same way, the stress distribution is analogous taking into consideration the cooling from outside and inside. Entirely different stress distributions can be obtained if the stresses are generated by crystallographic transformations. Bührer and Schell heated a high alloyed steel with $11.7 \% \text{Ni}$ to austenitizing temperature of $900^\circ\text{C}$ and cooled it slowly to $360^\circ\text{C}$, slightly above the austenite-ferrite transformation. Then the specimen was quenched in iced water. The transformation occurs first in the outer domain. The transformation is followed by an increase of volume. Thus compression is generated near the surface and tension is generated in the inner domain. Inside, the material deforms plastically. After the whole body has reached low temperature the outside domain contains compressive stresses, while the inside contains tensile stresses.

Different stress distributions can also be generated by mechanical treatment - for instance by drawing. Using dies with high reduction of cross section, tensile stresses are created in the outside domain and compressive stresses are created in the inside domain. If the work material has undergone another drawing process with only a very small reduction of area in the layers near the surface, compressive stresses are generated. By a specific combination of drawing steps the residual stress level can be mechanically lowered.

The phenomenon of stress generation can be followed over time. Fig. 20 shows three generating systems: a rolling process, where the surface is heated, and a quenching process with water cooling.

Residual stresses are mechanically generated by rolling. The roll is pressed on the workpiece thereby creating compressive stresses in the rolling direction. The material is plastically deformed. After the rolling process the surface layers are, without external forces, "too long" compared with the inside material. Compressive residual stresses are found in the outer surface layers, and lower tensile stresses are found inside the workpiece. The stress generation by drawing with little reduction of diameter is similar to this system.

Grinding with high metal removal rates and conventional grinding wheels usually results in compressive stresses. At the same time the yield strength is lowered so that the material is plastically deformed under the influence of compressive stresses. Then the temperature decreases and the surface layers are "too short". Tensile residual stresses are generated in the outer surface layers. Quenching creates a temperature gradient during the stress generating phase that is opposite to the above mentioned grinding process. It is assumed that no transformations of the face centred cubic lattice occur. During the cooling period the material near the surface shrinks, the inside material with low yield stress is plastically compressed. After temperature compensation, the inside layers are "too short", i.e. compressive stresses remain near the surface and tensile stresses remain inside. Thus, it is shown that by thermal impact tensile as well as compressive stresses can be generated. The governing condition is the temperature gradient during the residual stress determining phase.

3. Measurement

3.1 Methods

In many cases a classification of the measuring methods for residual stresses has been proposed as destructive or nondestructive. For a residual stress-depth-analysis all methods require a partial or complete destruction of the specimen; therefore a distinction as to direct and indirect measuring methods is more effective /2.32/.

For the indirect methods the equilibrium of forces and moments has to be disturbed so that the resulting deformations of the analyzed body or the removed part deliver the stresses which are of first order. The direct methods involve determination of stresses by measuring physical properties of the body which can be influenced by stresses. Deformation of the specimen is not necessary.

3.1.1 Indirect Methods

The first indirect method was proposed by Cilley /33/ for measuring the deformation of parts which are removed from the body to be analyzed. Due to the remaining stresses in the removed parts the results are, however, faulty. The remaining stresses decrease with the size of the divided parts, but the difficulty of measuring the deformations increases.

The problem can be overcome by measuring the deformation of the remaining part. The methods described by Sachs /34/ and Heyn and Bauer /35/ for cylindrical shapes of specimens as well as the methods of Stähelin /36/ and Treuting and Read /37/ for rectangular bodies are well known.

Simple shapes of specimens are chosen to keep the calculation effort small.

An approved method for practical application is the deflection method /2.32/ which has been applied for plates and cylinders. If machining stresses have to be determined the surface layers of the specimen are removed at the machined side while the deflections of the remaining part have to be measured as a function of thickness. For rectangular plates this principle is shown in fig. 21. If the principal directions of the residual stresses are known it is sufficient to measure the strains in just those directions. The stresses can be calculated according to:

Fig. 20: Types of residual stress generation
methods are based on the stress dependence of electric and magnetic properties of ferromagnetic materials. The application of which are, however, restricted to a few cases up till now. Electromagnetic methods depend in principle upon the fact that the propagation of ultrasound in a solid medium is influenced by the state of strain of the medium

\[ \sigma_{ij} = \frac{\partial u}{\partial x_j} \left( \frac{1}{2} \left( \frac{\partial \sigma_{ij}}{\partial x_k} + \frac{\partial \sigma_{jk}}{\partial x_i} - \frac{\partial \sigma_{ik}}{\partial x_j} \right) \right) \]

with the wave length of X-rays, the lattice spacing d and the diffraction angle \( \theta \) in order to receive interference with a maximum intensity at the detector in the loaded condition.

For technical materials which are polycrystalline, the lattice spacing d has to be determined for various grains which have the orientation relative to the specimen surface. This is possible for angles with \( -50^\circ < \Psi < 50^\circ \). By a mathematical extrapolation the lattice strains for \( \Psi = 90^\circ \) can be calculated. The stresses in this direction are to be determined by setting the lattice strains equal to those which the theory of elasticity would deliver for a biaxial surface stress condition, the basic equation of X-ray stress measurement results. Fig. 25 shows that in this case the lattice strains \( \varepsilon \) are a linear function of \( \sin^2 \Psi \). The factor \( 1/2 s^2 \) is called the X-ray elastic constant and has to be determined for the analyzed material in tensile or bending tests. It must be pointed out that this factor is not only dependent on the material but also on the heat treatment, plastic deformation and the radiation of X-rays.

The lattice strains \( \varepsilon \) can be calculated from the Bragg equation. This allows the very exact calculation of the peak positions from the diffracted intensities.
for different angles $\psi$. Several methods are available for this task /41, 43, 59-64/. Because of the little computation effort, the parabola method /59/ and the centre of gravity method /43/ are used in most of the cases. A new technique is given by the cross correlation method /41, 65/, which has essential advantages especially for computer controlled X-ray stress analysis /41, 53/.

For certain machining operations, especially those with a high degree of plastic deformation at the surface, the above mentioned linear dependence of $\sigma$ versus $\sin^2\psi$ is not observed /43, 56, 67/. This is due to a triaxial state of stress within the depth of penetration of the X-rays which is 5-20 $\mu$m. In these cases the multi- $\psi$ -angle-method has been applied. A goniometer set-up is necessary which is capable of measuring peaks for positive as well as negative $\psi$ -angles. If the distribution of $\sigma$ versus $\sin^2\psi$ is similar to an elliptic course, as it is very often the case for ground surfaces /68-70/, the evaluation method of Dalle and Hauk /71/ is suggested. The result is the complete stress tensor with nine components.

Besides the mentioned $\psi$-splitting there are also other nonlinear distributions possible which are not of a systematic nature. Surface texture is responsible for those effects and no evaluation method has yet been devised.

The X-ray method has advantages compared with the deflection method such as the feature of nondestructive surface measurements, variable measuring area, and the possibility for repeating measurements. On the other hand one of the disadvantages is the high time consumption. Using a goniometer with a proportional detector the measuring time for one stress value can be several hours. In recent years, however, several new ways have been shown to speed up the measurements:

1. Automatic control of the measuring process and the evaluation by computer
2. Determination of subsurface stresses by the slope method
3. Use of a position sensitive detector (PSD)

Computer controlled X-ray systems have been developed with different degrees of automation /41, 72/. The simplest standard is a goniometer control in order to measure one peak automatically. A high degree of development was reached by a linkage of the goniometer with digital computers /41/. Several measurements with job cues for different tasks are possible avoiding any type of slack time. Sample changers as well as turning and moving setups for the specimens have been installed.

Another time-consuming procedure is the determination of subsurface stresses by X-rays. Commonly the stress distribution as function of depth beneath the surface layer is determined by alternating stepwise electropolishing and measuring.

This method has two disadvantages, first, the operator must remove the specimen from the diffractometer for the etching procedures and clamp it again for the next measurement which means a loss of time, and second, it is impossible to repeat measurements later on, once the specimen has been etched. The slope etching method, which has been developed for this purpose, is highly advantageous /41, 53/. Fig. 26 shows the principle and the generation of the slope. An application with computer controlled X-ray equipment makes it possible to determine stress distributions beneath the surface automatically (fig. 27). Good agreement between the stepwise and the slope methods has been shown /41, 53/.

A further way to decrease the measuring time is the use of a position sensitive detector (PSD) instead of the conventional proportional counter /73-76/. While it is necessary for the proportional counter to scan the detector with the receiving slit along an arc in order to measure the diffraction peak intensity stepwise, this is not the case for the PSD which receives the entire peak at one shot (fig. 28). The high cost of this equipment should not restrict the application in the production process because the overall measuring time can be decreased at least 10 times.
3.2 Reliability and Results

To get an indication of the accuracy of the measurement, several samples were identically treated. They were ground in the same clamping on a surface grinder. The heat treatment and the grinding conditions are given in fig. 29. The deflections were determined by

![Material and grinding conditions for round robin test specimen](image)

Fig. 29: Material and grinding conditions of the round robin test specimen

the indirect method using strain gauges. The scatter from five analyzed specimens and the average stress are shown in fig. 30. These results reflect the influences of material inhomogeneities.

Several specimens of the identically treated samples, were also chosen for a round robin test in which several scientists in different countries participated. This test was proposed and carried out by the STC'S' of CIRP in order to find out the reliability of today's standard and state of the art in residual stress measurement. Both, indirect and direct methods were applied. Three groups were able to carry out indirect measurements, using the deflection method. The results are shown in fig. 31. It is evident, that not only the principal stress distribution but also the quantitative values show an excellent agreement. It has to be pointed out again that not only material and machining inhomogeneities but also different setups of the participating groups had their influence on the results. As an example, it should be mentioned that Hannover and Ljubljana used strain gauges for the measurement of deflection while Leuven applied mechanical sensors.

The X-ray users carried out surface measurements on a single round robin specimen. All of the five participants employed an \( \Omega \)-goniometer using CrK\( x \)-radiation. The X-ray elastic constant had been determined in one laboratory and the values was given to the participants. The measurement technique of the institutes was different in some points. While

1) The results are taken from a cooperative piece of work of STC'S' of CIRP on "residual stress measurements" in which the following scientists participated: Mr. J.B. Bryan, Livermore, Dr. M. Field, Cincinnati, Prof. W. König, Aachen, Prof. P. Leskovar, Ljubljana, Prof. J. Peters, Leuven, Prof. H.K. Tönshoff, Hannover

![Comparison of indirect stress measurement](image)

Fig. 31: Comparison of indirect stress measurement

Aachen and Hannover used the multi \( \varphi \)-angle method, the other laboratories considered only one branch of the \( \varphi \)-curve, respectively only two \( \omega \)-angles (B4E-method). Furthermore different methods for peak shift determination were applied.

Fig. 32 gives an overview of the evaluation techniques used. The results for the surface stresses parallel (\( \varphi = 90^\circ \)) to the grinding direction are summarized in fig. 33. The determined stress values show very good agreement; the differences are within ± 6 \( \% \).

A very remarkable result is that the surface stresses determined by X-rays, are considerably higher than the values determined by the indirect methods. Further information was obtained by comparing the complete stress distribution beneath the machined surfaces. For this purpose the slope method was applied for the X-ray measurements. The result parallel to the grinding direction can be taken from fig. 34 which demonstrates

![Data of X-ray stress measurement](image)

Fig. 32: Data of X-ray stress measurement

![Comparison of X-ray stress measurement](image)

Fig. 33: Comparison of X-ray stress measurement

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that the differences between the deflection and the X-ray method also exist beneath the surface.

Summarizing the most important findings, it can be stated:

1. Considering each measuring method alone, the results show very little scatter which is ± 10% in the worst case.

2. The qualitative stress distribution beneath the surface is the same for the indirect as well as the X-ray methods.

3. The quantitative stresses are considerably different. The X-ray values are about 30% systematically higher than the values from the indirect method.

The reasons for these differences may have their source either in the completely different measurement techniques or in the machining process, or in both of these. Several investigations were therefore carried out for clarification.

As the qualitative stress distribution is indeed very similar, the X-ray elastic constant was suspected to be incorrect. Extended investigations proved, however, that the value is correct within ± 5%. A bending as well as a tension test delivered equal results at the specimen surface. Even at a depth of 170 μm beneath the surface, the value was practically the same. Furthermore, the determined value fit into the experiences that other scientists had with the same material.

From the literature it is known, however, that a careful evaluation of an experimentally determined X-ray elastic constant is strongly recommended (54-57,77). This is due to the following facts:

1. Only those grains with lattice planes suitable for interference are considered in X-ray diffraction. Furthermore, in every polyphase material only lattice planes of one phase contribute to the strain determination. Different Young's moduli, for example in a pearlitic structure can be a source of faulty results.

2. An ideal isotropic elastic behaviour as it is presumed for the laws of elasto-mechanics, is not given for a crystalline material. This means that different X-ray elastic constants have to be applied for lattice planes with different Miller-indices. Especially for hardened materials with martensitic structure, a superposition of the diffraction from different planes is obtained. Since a separation is not possible, the determined constant is an average value.

For the indirect method the thickness of the glue layer, when using strain gauges, may be a source of systematic errors. It could be demonstrated that the thickness amounts to 48 μm ± 3 μm reproducible, which can be neglected, compared with the specimen's thickness of 4 mm.

A bending test revealed that the error of the strain values is less than 5% (fig. 35). It is further evident that an increasing glue layer thickness would deliver too high values of stress which is in contrast to the above-mentioned results.

While the indirect method is unable to detect local irregularities of stresses, this is possible for the X-ray method by adjusting the size of the focal spot. A large spot size gives an average stress value for the irradiated area. An averaging within the depth beneath the surface can be neglected since the depth of penetration of the Cr-radiation is only 5 μm. The influence of the focal spot size was therefore analyzed at the surface center of one test specimen. The irradiated area had been fixed up from 0.3 mm² to 90 mm² which includes a factor of 300. The scatter of the determined stresses was, however, ± 3% only (fig. 36). This proves a constant magnitude of stress at the specimen surface center.

The next step was to take advantage of the variable spot size in order to control whether the machining process produces irregularities in stress distribution at any spot of the specimen. A scanning of the surface across the length with a small spot size revealed a stress distribution as shown in fig. 37. It is evident that the thermal impact upon the specimen surface increases considerably after the beginning of the cutting process. Similar results had also been obtained by Provey and Field [28]. A steady state of influences is reached after 20 mm distance from one edge of the specimen. As the strain gauges for the indirect method had been fixed at the centre of the sample, it may be possible that the measured deflection was an average value including also lower stresses from the inhomogeneous distribution. This is confirmed by the fact that the stress analysis of specimen with homogeneous stress distribution, reached by other grinding conditions, delivered an essentially better agreement between the indirect and the X-ray methods.

4. Residual Stresses by Machining

4.1 Thermal and Mechanical Impacts
Another example for a purely mechanical impact is the Fig. chining direction in contrast to shot peening. Rolling beneath the peened surface.

radius is commonly used to limit the domain of compressive stresses to a small rolling process /81,82/ which has a preferential ma-
sidual stress distribution where the maximum of the domain of stresses can have their maximum also some micrometers beneath the surface, the compressive plastic deformation /73,78-80/. The penetration of penetration depth of the residual stresses depends upon the pee-
component a desired shape and quality of surface. As
ditional machining operations, which will be men-
A typical practical example for a mainly mechanical iri-
the formation of microcracks at the surface.
A thermal impabt on a surface leads, in contrast to
A good example is electro-discharge machining (EDM) /86,87/ which always leads to tensile stresses (fig. 43) /86/. The amount of stresses and the depth of penetration are dependent on the discharge energy (fig. 44). Very often a stress relaxation can be observed when applying high energies. This is due to the formation of microcracks at the surface.

To complete the possible impacts by machining, the chemical attack on a surface should also be mentioned. In general, however, no new stresses are generated /80/.

Additional machining operations, which will be men-
Fig. 37: Residual stress profile on ground specimen

Machining processes are applied in order to give a component a desired shape and quality of surface. As the functional behaviour of machine parts is in many applications substantially determined by the state of the surface, the latter has to be given special con-
consideration in the machining process. A complete de-
scription of the surface is given by the geometrical and physical properties. While the geometrical proper-
ies are well known for many machining conditions, this is not necessary true for physical properties such as residual stresses, hardness and structure of the surface layers. Field and Kahales /1/ defined the notation "surface integrity" which gives a relationship between the physical properties and the function-
al behaviour of a surface. In a machining process the surface integrity is determined by mechanical, thermal and chemical interrelationships between the tool and the workpiece. Fig. 37 shows which parameters are able to influence those impacts.

Usually mechanical, thermal and chemical impacts are acting at the same time with overlapping influences. This leads to residual stress distributions which can, therefore, not be correlated to one impact. Consider-
ing each impact alone, characteristic results can be obtained as was already mentioned in section 2, fig.19. A typical practical example for a mainly mechanical in-
fluence is the shot peening process which always re-
results in compressive stresses at the surface due to the plastic deformation /73,78-80/. The penetration depth of the residual stresses depends upon the pee-
component a desired shape and quality of surface. As
Fig. 38: Surface impacts in a machining process

obtained as was already mentioned in section 2, fig.19. A typical practical example for a mainly mechanical in-
fluence is the shot peening process which always re-
results in compressive stresses at the surface due to the plastic deformation /73,78-80/. The penetration depth of the residual stresses depends upon the pee-
component a desired shape and quality of surface. As
Fig. 39: Residual stresses in shot peening

sharp range on the saw blade. Components which are loaded by rolling are the elements of roller bearings. Due to the rolling a plastic deformation of the sur-
face layers is caused which results in compressive stresses. The penetration depth of the stresses in-
comparison with the number of revolutions (fig. 41) /82/.

Compared with the latter machining operations, the abrasive tumbling process produces an essentially lower degree of plastic deformation /84/. It is used for example for improving the surface quality of cast parts by removing burrs. The tumbling of ground work-

Fig. 40: Residual stresses in a circular saw blade by rolling

shown. A good example is electro-discharge machining (EDM) /86,87/ which always leads to tensile stresses (fig. 43) /86/. The amount of stresses and the depth of penetration are dependent on the discharge energy (fig. 44). Very often a stress relaxation can be ob-
served when applying high energies. This is due to the formation of microcracks at the surface.

To complete the possible impacts by machining, the chemical attack on a surface should also be mentioned. In general, however, no new stresses are generated /80/.

Additional machining operations, which will be men-
mentioned in the following, are characterized by a super-
lead to residual stresses which reach from tension to compression depending on the machining condition, tool and workpiece material.

Various scientists have developed models which should be able to predict the machining residual stresses in the workpiece. Rather a simple model has been explained by Syren /25/. Syren distinguishes between surfaces which are cut by the tool without a following squeezing and those, which are squeezed and thus plastically deformed after the cutting process. Syren states: "Surfaces generated by a cutting operation without a following squeezing have tensile stresses. Tensile stresses shift towards compression if the magnitude of the squeezed surface elements increases. High cutting temperatures will favor tensile stresses. Blunt cutting tools can also lead to compressive stresses by a bigger surface deformation and can produce tensile stresses because of an increasing of friction." Syren proves this theory by measuring residual stresses produced by different machining processes. While the model is very suitable to explain f.i. the different stresses produced by up cut milling and down cut milling, it is not sufficient to give a useful description of the conditions in grinding. This special problem had been tackled by Snoeys, Maris and Peters /80/. The model is based upon the research work of Jaeger /09/ and gives a relationship between the kinematic grinding parameters and the surface temperature of the workpiece. For a given wheel-work-cooling-dressing condition, the influence of the kinematic parameters is governed largely by the variation of the tangential grinding force which determines, together with the grinding speed, the specific energy of the grinding process. Related to the equivalent wheel diameter \( d_e \), the force equation can be written

\[ F_t = F_0 \cdot h_{eq} \cdot \left( \frac{v_c}{v_t} \right)^{0.1} \cdot d_e^{(1-f)} \]

with the force exponent \( 0.3 < f < 1.0 \) and the equivalent chip thickness \( h_{eq} = a \cdot V_t \). If \( f \) has been determined by the upper equation, the contact temperature \( T \) can be calculated principally as follows:

\[ T \approx a^{2.35} \cdot v_t^{0.57} \cdot v_c^{1.11-f} \cdot d_e^{0.765-f} \]

It can be seen that the force exponent \( f \) is a particularly important factor, as it reflects the dependence of tangential forces upon the machining parameters and thus upon the temperature rise in the workpiece. An important recognition is that a single machining parameter is without any influences upon the temperature if the force exponent has a certain value. Fig. 45 gives an impression of the qualitative dependence of the temperature from the stock removal rate \( E \) (as a function of workspeed) and the cutting speed for material-wheel combinations with different \( f \)-values. Materials which are difficult to grind are characterized by a low force exponent which leads to high temperatures and thus to tensile stresses. It can be shown that the amount of maximum tensile stresses in a machined surface is dependent on the maximum surface temperature /88/. Fig. 46 demonstrates this relationship for two different types of steels. The influence of structural changes is also evident.
4.2 Grinding

In grinding operations, randomly distributed abrasive particles of various geometrical forms, varying in their cutting characteristics, produce plastic deformations on the surface of the machined parts. The normal pressures produced during grinding are high compared with other machining operations. High temperatures and pressures in the zone of interaction between the grains and the workpiece material and heavy plastic deformation of the latter lead to substantial changes of the physical properties. Thus the produced residual stresses are influenced by the following parameters:

- machining conditions (depth of cut $a$, speed of workpiece $v_{w}$, cutting speed $v_{c}$)
- topography of the grinding wheel (dressing conditions, wear behaviour)
- specification of the grinding wheel (type and size of grains, structure, bond, hardness)
- cooling conditions

The influence of the machining conditions has been analyzed by various scientists /1,2,23-26,41,90-107/. In most cases conventional aluminium oxide wheels have been applied.

The related material removal rate $Z'$ is given by the product of speed of workpiece $V_{w}$ and depth of cut. These two factors show inverse effects on the machined surface. Increasing the depth of cut leads to higher tangential forces and, thus, to stresses towards tension due to the increased cutting energy. An increased speed of workpiece leads to faster movement of the heat source along the machined surface. For different parameters this behaviour is demonstrated in fig. 47 for plunge grinding /48/.

Since the cutting energy and thus the heat which is produced in the cutting zone are given by the tangential forces and the cutting speed, the latter is a very important parameter also affecting residual stresses. For a titanium alloy, fig. 48 shows that the magnitude of surface stresses is mainly influenced by the wheel speed /90/. The wheel dressing is found to be a parameter with a great impact upon the grinding wheel topography with a great impact upon the grinding wheel topography and thus upon the heat generation in the cutting process. Although it is well known that the dressing conditions are 2 to 3 times more critical than other parameters /90/ only a few investigations have been carried out /41,104-106/. It can be assumed that different results according to absolute values of residual stresses in grinding with comparable conditions react back to this influence. Fig. 49 gives an example of the dressing influence /41/. Coarse dressing produces a wheel surface that is open and free cutting. On the other hand, a closed grain structure in the wheel results in wheel surfaces that are not free cutting which leads to an increased thermal impact. Tensile residual stresses increase although the surface quality is improved in most cases. Of a similar importance is the wear of the grinding wheel /93,104,107/. Aluminium oxide wheels are especially sensitive to this effect. In many applications a blunting of grains can be detected already after a short grinding time. Fig. 50 /41/ shows that the low stresses after dressing become rather high tensile stresses after a removed workpiece volume of $V_{w} = 100 \text{ mm}^3/\text{mm}$. Furthermore, the influence of the cutting speed increases with the wear. Similar results have been found by Peters /107/.

Fig. 46: Relationship of temperature effects and residual tensile stresses

Fig. 47: Residual stresses after plunge grinding

Fig. 48: Cutting speed and residual stress

Fig. 49: Dressing conditions and residual stresses

Fig. 50: Residual stresses as function of grinding wheel wear and cutting speed
For residual stress generation, not only is the condition of the wheel while in use important, but also the selection of grains, bond, structure and hardness. A soft wheel can require more dressing time, particularly in form grinding; however, it can be advantageous to use because less stress is produced. This is due to the fact that grain blunting, which means heat generation by friction, cannot arise because a grain breaks out if the tangential force exceeds a certain value. In contrast to the conventional aluminium-oxide wheel, the wear behaviour from cubic boron nitride (CBN) wheels is completely different. This has been proved in surface grinding /41/ and in internal grinding /104/. Due to the high hardness of CBN, no blunting could be observed with the scanning electron microscope but only splintering which does not restrict the sharpness. Therefore, less heat arises in the cutting zone with the consequence that only compressive residual stresses are produced. With increasing CBN-concentration of the wheel, the residual surface stresses shift to compression. For comparison purposes, results for an aluminium-oxide wheel are also given in fig. 51. It is evident that constant reliable stresses are produced for a long grinding period.

There are several known methods for improving the residual stress conditions of ground surfaces. Most of these methods are finishing operations which rely primarily on plastic surface deformation with little metal removal. One of them is the sparking out procedure in the last grinding cycles. Fig. 53 /41/ demonstrates that a considerable stress relaxation is achievable by this operation.

Another finishing method is the abrasive tumbling of ground surfaces which has been explained previously. A procedure which is very often applied by ball bearing manufacturers is the honing process. Fig. 54 gives an idea of the honing effect applied on external ground workpieces. The predominant plastic deformations are able to produce high compressive stresses /94/.  

4.3 Turning

In turning operations the cutting energy is mainly transformed in the shearing zone. This enables the produced heat to flow not only into the workpiece surface but also into the chips. Although the heat which flows off with the chips is greater per volume element than in grinding, tensile residual stresses are dominant in turning /2,73,108-111/. This is due to the fact that the machined surface is usually not produced by the main cutting edge but by the secondary cutting edge. It has been proved that the friction induced forces and thus the cutting temperatures increase with the tool radius and the cutting speed. A smaller chip thickness and negative cutting angles produce the same result due to higher friction /112/. On the other hand, a negative cutting angle produces a higher degree of plastic deformation (fig. 55) which results in a decreasing of surface tensile stresses (fig. 56) /2/.

Not only the mechanical but also the thermal impact increases with the cutting feed \( f \). This results in higher tensile stresses at the surface and a deeper penetration of stresses into the material (fig. 57) /2/.
A further example from practice is the tungsten carbide tip turning of an aluminium alloy. Tubes with 70 mm diameter had been produced by a manufacturer by cold extrusion. One customer applied those tubes for transferring chemical fluids after having machined the tubes inside as well as outside by turning. A stress corrosion problem arose after some time which could be attributed to the machining operation /11/.

From the tube suitable specimens were cut out and analyzed by the X-ray diffraction method. Fig. 58 shows the surface stresses of the unmachined as well as the machined tube. It can be seen that the cold extrusion of the manufacturer leads to compressive stresses and negligible tensile stresses, while the turning operation produces considerable tensile stresses.

4.4 Milling

In milling, considerable plastic deformation is produced, thus the residual stresses tend to be compressive /1,2,25,73,108,109,113,114/. Since the penetration depth of thermal influences upon the surface are smaller than the mechanical impacts, the compressive stresses are reduced at the surface and may even rise to tensile stresses. Typical stress distributions for face milling are shown in fig. 59 /113/.

Higher cutting speeds and feed rates lead to an increase of compressive stresses and depth of penetration. In milling, the wear of the cutting tool is of significant influence. The duller the tool, the deeper the compressively stressed layer. In fig. 60 /1/ the sharpness of the tool is characterized by the wearland. Similar results had been obtained by Klein /109/ and Byron /25/. Syren explains different stress distributions by means of his developed model considering thermal and mechanical impacts. The model can also efficiently be applied for explaining different residual stress distributions in up cut milling and down cut milling as it has also been proved by Kiethe /114/. In up cut milling a cold cutting edge enters the cutting process with a very small chip thickness. Cold plastic deformations are dominant at the machined surface and lead to compressive stresses. During the further contact length of the tooth, the produced heat increases in those surface layers, which are re-
moved by the next tooth. In down cut milling the cutting process starts with the maximum chip thickness. During the contact length the temperature rises. The cutting edge leaves the shearing zone, transducing the heat into the machined surface and thus producing tensile stresses. The model can be proved by measuring residual stresses at different points of the cutting arc. Fig. 61 shows stress distributions, measured at three points in up cut milling /114/. The rise in temperature during the shearing process is clearly evident. Turning to the results in down cut milling tensile stresses remain only which remain in the machined surface in agreement with the explained model (Fig. 62).

In machining processes residual stresses can be generated by mechanical, thermal and transformation causes. Thus, characteristic stress distributions are developed. In practice these causes amalgamate and can vary in wide ranges.

Fig. 61: Residual stresses in up cut milling at different points of the cutting arc (Kiethe)

4.5 Shaping

The principal stress distributions in shaped surfaces are comparable with those produced by turning. The essential difference from milling is the continuous cut. While the discontinuous cut in milling can produce compressive stresses (up cut milling), in shaping operations tensile stresses are dominant /2,25/. Syren /25/ analyzed the cut-in and the cut-out conditions by shaping key arranged specimens (Fig. 63). It can be seen that the zone of plastic deformation with compressive stresses is rather small and tensile stresses are produced after a short cutting length as soon as the chip formation is started.

5. Conclusions

Residual stresses in surface layers of a machined component can generate deformations and can influence the static and dynamic strength and the magnetic and chemical properties of the surface. A complete description of a machined surface requires, therefore, determination of the residual stress tensor. This tensor can always be considered as caused by the action of residual strains and from strains which are subjected to the compatibility conditions.

The measurement of residual stresses generated by machining is difficult because of the steep gradients perpendicular to the surface. X-ray (direct measurement of lattice spacing) and deflection techniques (indirect measurement) were applied by several laboratories. The results are in good agreement; yet it has to be considered that the deflection method is an integral measuring procedure whereas the X-ray method needs only a limited measuring spot.

Shot peening and rolling are typical mechanically influencing processes, electro discharge machining (EDM) influences thermally. The characteristic stress distributions were shown: compressive stresses with equal tensor components by shot peening, also compressive stresses by rolling but with distinct principal directions, EDM generates equal tensile components. For other machining processes like grinding, honing, turning, milling and shaping characteristic stress distributions were given.

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