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Abstract: In the research concept of Process Signatures machining induced changes of surface and sub-surface material properties are considered as material modifications caused by the physical conditions the material is exposed to during the process. This paper presents a newly developed multilayer source stress model to analytically describe the

An analytical multilayer source stress approach for the modelling of material modifications in machining

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In the research concept of Process Signatures machining induced changes of surface and sub-surface material properties are considered as material modifications caused by the physical conditions the material is exposed to during the process. This paper presents a newly developed multilayer source stress model to analytically describe the material modifications caused by the machining proces in multiple passes. The analytical model that needs measured shape deviations as input is validated via finite element simulations. The approach incorporates the effects of machining induced source stresses and the contribution of residual stresses present in the workpiece before machining. Results from milling experiments show a pronounced correlation between the identified workpi ce material modifications and the width of cut.

Machining, residual tress, modelling

1. Introduction

Great effort has been taken in science and industry to improve the functional performance of components. It was found that there is a strong link between the surface integrity of the machined components and their lifespan under different loads [1]. Surface integrity depends amongst others on hardness, microstructure and residual stresses [2]. Within the concept of Process Signatures these characteristic quantities are called state variables [3]. Especially the residual stresses present in a workpiece before and after machining have a major influence on the distortion potential, the fatigue strength and thus the quality of the machined part. It is therefore desirable to find reliable and cost-effective methods to determine residual stresses present in workpieces [4, 5].

Many different characterisation methods have been developed to approach the residual stress state of workpieces. These methods can generally be divided into two categories: diffraction methods and mechanical relaxation methods [6, 7].

Diffraction methods can be used to measure residual stresses at fixed points near the surface and are destructive if residual stresses in the bulk material need to be accessed. It is therefore rather time consuming and expensive to measure the entire residual stress field of a workpiece.

Mechanical relaxation methods are more suitable for macroscopic measurements and can be used to estimate entire stress fields from measured workpiece deformations caused by a layer-wise material removal and the utilisation of a related analytical or numerical model. The material removal necessary to initiate mechanical relaxation is in many cases carried out with electrolytic etching to avoid new plastic deformations introduced by the material removal. Another approach is the material removal by a conventional machining process with a correction of the results by additional x-ray diffraction measurements of the residual stresses introduced by the machining process [8].

In summary, it is important to develop an effective method to determine the bulk residual stress and the stress originating from the machining process at the same time in order to describe the resulting material modifications for varying cutting conditions.

In 1931 Reißner introduced so-called stress sources describing the effects of a plastically deformed layer on residual stress [9]. Based on this Tönshoff characterised the residual stresses for different machining processes and introduced the notion of source stresses [10]. Brinksmeier and Sölter et al. developed a very efficient approach for the characterisation of machining induced source stresses [11, 12]. Source stresses are constant over the penetration depth z_0 and are equal to the stresses required to cause the measurable shape change. In general the penetration depth z_0 coincides with the thickness of the plastically deformed layer caused by the machining process. If this thickness cannot be determined, the penetration depth can be assumed to be an arbitrary value and source stresses become effective source stresses [13]. However, this method assumes an initially residual stress free workpiece which is difficult to achieve in practice.

2. Objectives and procedure

2.1 Objectives

The research presented in this paper aims at the development of an analytical approach to determine machining induced effective source stresses and the residual stresses present in the workpiece before machining at the same time.

2.2 Development of an analytical multilayer source stress model

In order to model the workpiece behaviour associated with machining induced residual stresses a source stress model using a single source stress layer was developed in previous research [13]. The model assumes that constant effective source stresses as a result of the machining process affect the surface layer of the machined workpiece up to a constant penetration depth z_0. With the assumption of an otherwise residual stress free workpiece the effective source stresses $\sigma_{source,m,x}$, $\sigma_{source,m,y}$ and $\tau_{source,m,xy}$ needed to cause the measured shape deviation ($\partial^2 w/\partial x^2$, $\partial^2 w/\partial y^2$ and $\partial^2 w/(\partial x \partial y)$: bending in x and y direction, torsion) of a thin plate can be calculated. Although the model is very efficient for the calculation of machining induced shape deviations, the main drawback is the simplifying assumption of nearly residual stress free workpieces for the determination of machining induced source stresses.

Because perfectly residual stress free workpieces are very difficult to manufacture, the overall residual stress state of the workpiece is always altered by the removal of stress sources present in the stock to be removed. It is therefore more accurate to incorporate the workpiece inherent residual stresses by modelling the workpiece as a compound of several layers each containing an individual set of constant source stresses. In this way the overall curvature and torsion of the modelled thin plate is influenced by the plate stiffness and the contribution of the bending and torsion moments of each layer.

The equations describing the effective source stresses $\sigma_{source.m,x}$, $\sigma_{source.m,y}$ and $\tau_{source.m,xy}$ are solved for the curvature terms $\partial^2 w/\partial x^2$, $\partial^2 w/\partial y^2$ and $\partial^2 w/(\partial x \partial y)$ taken from [13] respectively:

$$\frac{\partial^2 w}{\partial (x/y)^2} = \frac{(\sigma_{source.m,x/y} \cdot z_0 - \nu \cdot \sigma_{source.m,y/x} \cdot z_0) \cdot \left(\frac{T}{2} - \frac{z_0}{2}\right)}{K \cdot (1-\nu^2)} \quad (1)$$

$$\frac{\partial^2 w}{\partial x \partial y} = \frac{\tau_{source.m,xy} \cdot z_0 \cdot \left(\frac{T}{2} - \frac{z_0}{2}\right)}{K \cdot (1-\nu)} \quad (2)$$

The equations 1-2 describe the curvature and torsion of an initially residual stress free thin plate influenced by one layer containing the stresses $\sigma_{source.m,x}$, $\sigma_{source.m,y}$ and $\tau_{source.m,xy}$. From the equations it can be seen that the curvature is a function of forces per unit width, e.g. $\sigma_{source.m,x} \cdot z_0$, the lever arm $h = \left(\frac{T}{2} - \frac{z_0}{2}\right)$ and the terms $K \cdot (1-\nu^2)$ and $K \cdot (1-\nu)$, where K denotes the plate stiffness $K = \frac{E \cdot T^3}{12 \cdot (1-\nu^2)}$.

In order to extend the original model to a multilayer source stress model the curvature of the workpiece is expressed as the sum of individual bending moments caused by the source stresses $\sigma_{source.wp,i,x}$, $\sigma_{source.wp,i,y}$ and $\tau_{source.wp,i,xy}$ (Eq. 3-4) acting in m layers of thickness $z_{0,i}$ with the lever arms h_i. The sum of the individual layer thicknesses equals the plate thickness $T = \sum_{i=1}^{m} z_{0,i}$ (Fig. 1).

$$\frac{\partial^2 w}{\partial (x/y)^2} = \frac{\sum_{i=1}^{m} (\sigma_{source.wp,i,x/y} \cdot z_{0,i} - \nu \cdot \sigma_{source.wp,i,y/x} \cdot z_{0,i}) \cdot h_i}{K \cdot (1-\nu^2)} \quad (3)$$

$$\frac{\partial^2 w}{\partial x \partial y} = \frac{\sum_{i=1}^{m} \tau_{source.wp,i,xy} \cdot z_{0,i} \cdot h_i}{K \cdot (1-\nu)} \quad (4)$$

Another set of equations ensure the force equilibrium in the initial workpiece:

$$0 = \sum_{i=1}^{m} \sigma_{source.wp,i,x/y} \cdot z_{0,i} \quad (5)$$

$$0 = \sum_{i=1}^{m} \tau_{source.wp,i,xy} \cdot z_{0,i} \quad (6)$$

The moment equilibrium is ensured by assuming a symmetric arrangement of layers with respect to the neutral plane.

The appropriate lever arms h_i are calculated from the current geometry and have negative values for the layers beneath the neutral plane to account for the direction of the resulting bending and torsion moments.

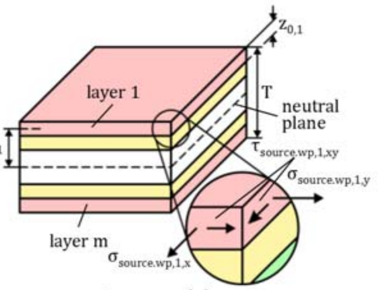

Figure 1. Multilayer source stress model.

2.3 Complementary experimental and modelling procedure

In order to determine machining induced source stresses and model the initial residual stress state of the considered specimens the multilayer source stress model was adapted to workpieces of a thickness T = 12 mm which would be machined four times, each time removing a layer of the thickness which corresponds to the depth of cut a_p = 1 mm from the top (Fig. 2).

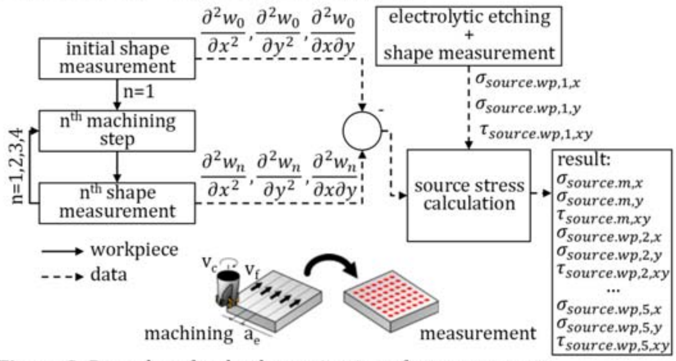

Figure 2. Procedure for the determination of source stresses.

For the considered scenario a workpiece (thin plate) with a symmetrical residual stress profile was assumed. In this work the adopted model consists in total of 9 layers: four layers of the thickness $z_{0,1} = z_{0,2} = z_{0,3} = z_{0,4} = a_p$ = 1 mm, one layer of thickness $z_{0,5} = T\text{-}2\cdot(4\cdot a_p)$ = 4 mm and another four layers of the thickness $z_{0,6} = z_{0,7} = z_{0,8} = z_{0,9} = a_p$ = 1 mm (Fig. 3).

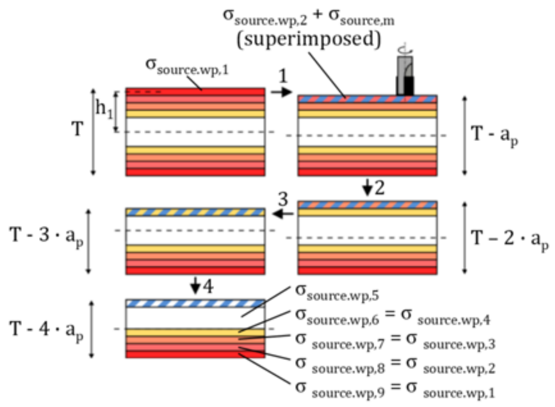

Figure 3. Machining and modelling procedure for the determination of machining induced source stresses.

When symmetry is considered (Eq. 7-8) the model contains a total of 18 unknown source stresses including the machining induced source stresses $\sigma_{source.m,x}$, $\sigma_{source.m,y}$ and $\tau_{source.m,xy}$. Therefore, 18 linearly independent equations are needed for the solution.

$$\sigma_{source.wp,5-n,x/y} = \sigma_{source.wp,5+n,x/y} \quad (7)$$

$$\tau_{source.wp,5-n,xy} = \tau_{source.wp,5+n,xy} \quad (8)$$

$$n = 1, 2, 3, 4$$

In the initial state three equations are derived from the force equilibrium (Eq. 5-6). The remaining four states add twelve equations, three for each state, describing the shape change of the workpiece (according to Eq. 3-4). The last three equations are obtained from the separate measurement of the source stresses in the very first layer, e.g. by electrolytic etching or x ray diffractometry. The resulting system of linear equations is solvable with the following assumptions:

- The milling process in each step is executed with identical machining parameters leading to the same machining induced source stresses $\sigma_{source.m,x}$, $\sigma_{source.m,y}$ and $\tau_{source.m,xy}$.
- The depth of cut (a_p = 1 mm) is higher than the thickness of the plastically deformed surface layer of the preceding cut.
- The workpiece inherent residual stresses do not influence the machining induced source stresses, superposition applies.

2.4 Model validation

The implementation of the multilayer source stress model was validated with a set of arbitrarily chosen source stresses utilising a finite element model according to [13]. The modelled workpieces had the dimensions 50 mm · 50 mm · (T - n · a_p) and consisted of $2.2 \cdot 10^6$ to $3 \cdot 10^6$ finite elements. A modulus of elasticity of E = 212000 N/mm² and a Poisson`s ratio of ν = 0.3 were used for the analytical and the finite element model.

The finite element model is applied to calculate the bending and torsion of thin plates according to the machining steps shown in Fig. 3. The calculated values for $\partial^2 w/\partial x^2$, $\partial^2 w/\partial y^2$ and $\partial^2 w/(\partial x \partial y)$ in each step together with the assumed source stresses of the first layer $\sigma_{source.wp,1,x}$, $\sigma_{source.wp,1,y}$ and $\tau_{source.wp,1,xy}$ were used to solve the system of linear equations for the source stresses in the different workpiece layers and for the machining induced source stresses (Fig. 4).

2.5 Experimental setup

The workpieces were made of normalised 42CrMo4 steel (AISI 4140). They were sawn from the central region of premachined and normalised prismatic bars with a width a = 145.2 mm, a height b = 145.2 mm and a length l = 500 mm. The specimens had a thickness of $T = \Delta l$ = 12 mm. Care was taken to ensure a symmetrical sawing operation from both sides generating equal premachining induced initial residual stress profiles. The variation of material characteristics over the specimen thickness was regarded to be negligible.

The milling experiments were conducted in down-milling mode. For each cut the milling tool was set back in feed direction and shifted lengthwise according to the width of cut a_e (Fig. 2). The cutting was repeated until one workpiece layer was removed from the specimen. The milling tool was an indexable square shoulder face mill with inserts made of tungsten carbide. The cutting inserts were replaced after machining five workpiece layers.

20 workpieces were analysed in the milling experiments, machining each workpiece four times and measuring the curvature and torsion of the lower unmachined surface five times. A constant cutting speed of v_c = 373 m/min, a constant feed speed of v_f = 2800 mm/min and a constant depth of cut of a_p = 1 mm were applied. The width of cut a_e was varied on four levels (0.95 mm, 3.66 mm, 7.72 mm, 12.5 mm). Each parameter set was repeated five times.

The source stresses in the first layer $\sigma_{source.wp,1,x}$, $\sigma_{source.wp,1,y}$ and $\tau_{source.wp,1,xy}$ were obtained by electrolytic etching of an additional specimen. This way the first layer could be removed without introducing additional source stresses allowing the calculation of the workpiece source stresses in the first layer from the measured shape change.

3. Results and Discussion

3.1 Model validation

A very close agreement was found with a maximum and an average difference of 6.9 % and 2.0 % respectively. Due to the small error, the implementation of the multilayer source stress is considered to be validated (Fig. 4).

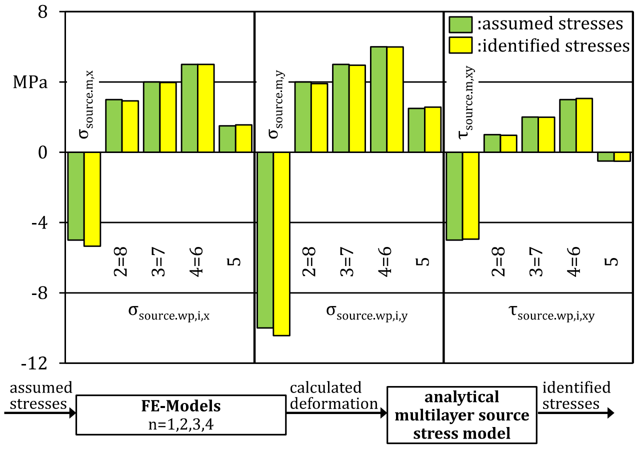

Figure 4. Assumed and identified source stresses for model validation.

3.2 Workpiece inherent stresses before machining

The workpiece inherent and machining induced source stresses were obtained with the validated implementation of the multilayer source stress model, the measured workpiece deformations after the cutting experiments and the source stresses obtained by electrolytic etching.

Evaluation of the experimentally determined source stresses present in the workpiece before machining (Fig. 5) shows that the sawing of the workpieces accounts for relatively high compressive source stresses in the top surface layer. The direction of $\sigma_{source.wp,1,x}$ = -15.9 MPa was aligned with the feed direction and $\sigma_{source.wp,1,y}$ = -2.8 MPa with the cutting direction in sawing. The sawing also produced a considerable torsion source stress of $\tau_{source.wp,1,xy}$ = -2.6 MPa. All other workpiece inherent source stresses which correspond to layers lying on the inside show relatively small tensile source stresses. This distribution is expected for a workpiece of an almost residual stress free state after normalisation that is influenced by a process like sawing with a predominant mechanical impact.

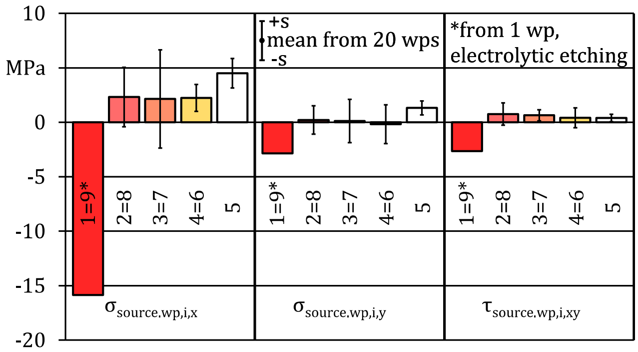

Figure 5. Workpiece (wp) inherent source stresses.

3.3 Machining induced source stresses

Fig. 6 shows the calculated machining induced source stresses for different widths of cut. Although the four sets of machining parameters use the same depth of cut, cutting velocity and feed velocity, the internal material loads are expected to vary considerably over the cutting arc, with a variation of the uncut chip thickness h = 0…0.15 mm. The different widths of cut used in the experiments cover an increasing fraction of the cutting arc, with a_e = 0.95 mm containing only the smallest part and a_e = 12.5 mm = ½ *tool diameter* the whole cutting arc.

When the smallest width of cut of a_e = 0.95 mm is used the cutting occurs at the thin end of the chip where a relatively inefficient cutting with severe plastic deformations is expected. This leads to more compressive source stresses than found for the other widths of cut used. The material modifications caused by the milling process shift from compressive to tensile machining induced source stresses with higher widths of cut. This can be observed most clearly for $\sigma_{source.m,y}$.

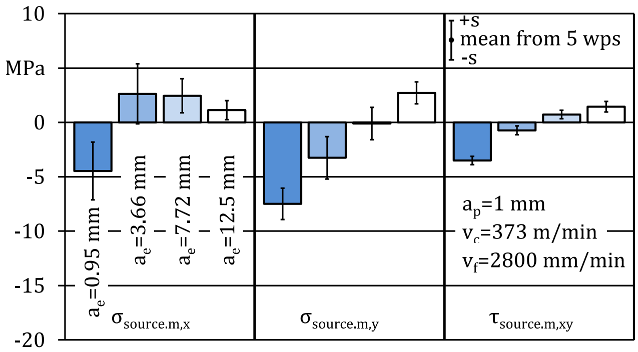

Figure 6. Machining induced source stresses for $z_{0,m}$ = 1 mm.

3.4 Residual stresses after multiple milling passes

The determined source stresses can be utilised to calculate the workpiece deformations after multiple cutting passes. It is also possible to obtain an approximation of the in depth residual stress state of the workpieces after each cut (Fig. 7), e.g. by finite element simulations. As expected the relaxation of the workpiece leads to the superposition of workpiece source stresses, constant compensation stresses and linear bending stresses and each machining step influences the stresses in every layer of the model.

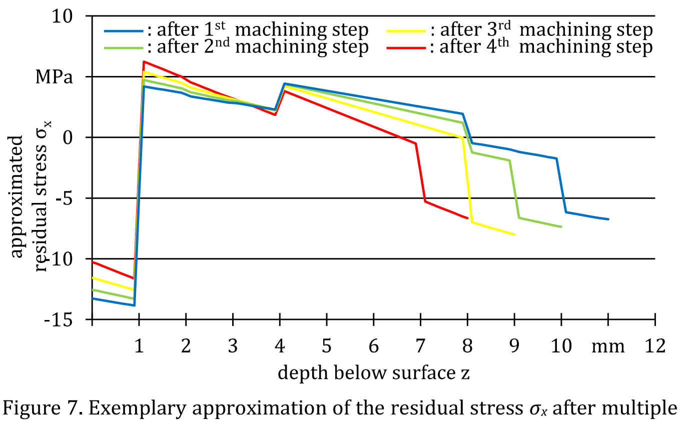

Figure 7. Exemplary approximation of the residual stress σ_x after multiple milling passes with the width of cut a_e = 0.95 mm.

4. Conclusions and outlook

In order to determine material modifications due to machining induced local plastic deformations of the surface layer an existing source stress model was extended to a multilayer model which can account for workpiece inherent source stresses throughout the whole part. The extended model was validated by means of finite element simulations and was used to determine milling induced source stresses and the in depth stress distribution of the workpieces.

The results indicate a strong dependence of the milling induced source stresses on the width of cut used to machine the surfaces. The observed effects can be explained with the varying undeformed chip thickness along the cutting arc.

Further research should aim at the identification of internal material loads, especially strain fields in the surface layer during machining, either by measurement or simulation, in order to establish a direct link between the internal material loads and the resulting material modifications (Process Signatures).

The source stresses in the surface layer after machining directly represent the distortion potential for the given machining parameters. When a relaxation simulation with the obtained source stresses as input variables is carried out, an approximation of the resulting residual stress state after machining can be obtained for every layer after every machining step. However, the resolution of the profile is limited to the depth of cut used in the experiments. In order to obtain more accurate residual stress profiles, the method will be enhanced to allow for smaller depths of cuts by the determination of the thickness of the machining affected layer z_0. A further decrease of the depth of cut below z_0, providing a higher spatial resolution, will be realised once additional models that take into account multiple influences of subsequent cuts on the material modifications of a workpiece surface layer are developed.

5. Acknowledgements

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