

Influence of process and geometry parameters on the surface layer state after roller burnishing of IN718

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Abstract Highly stressed components of modern aircraft engines, like fan and compressor blades, have to satisfy stringent requirements regarding durability and reliability. The induction of compressive residual stresses and strain hardening in the surface layer of these components has proven as a very promising method to significantly increase their fatigue resistance. The required surface layer properties can be achieved by the roller burnishing process, which is characterised by high and deeply reaching compressive residual stresses, high strain hardening and excellent surface quality. In order to achieve a defined state of the surface layer, the determination of optimal process parameters for a given task still requires an elaborate experimental set-up and subsequent time-consuming and cost-extensive measurements. The development of well funded process knowledge about the correlation of the process parameters, the processed geometry and the surface layer state is the subject of this article.

Keywords Production process Roller burnishing
Compressor blades

1 Introduction

Highly stressed components of modern aircraft engines, like compressor and turbine blades, have to satisfy

stringent requirements regarding durability and reliability. An additional attenuation can be induced by small damages caused by unavoidable impacts of foreign objects on heavily loaded turbojet engine components, like fan and compressor blades. This can result in oscillating fatigue and breakage during continued operation. This type of damage represents more than 25% of the most frequent causes for cost-extensive engine overhauling [12].

Previous research results [2, 10, 11] show that applying a mechanical strain to harden the surface layer leads to a significant increase of the damage tolerance. Such a treatment can be achieved with the production process roller burnishing. This process distinguishes itself by substantial advantages from other mechanical strain hardening methods like high and deeply reaching compressive residual stresses, high strain hardening and excellent surface quality [11]. A comparison of different strain hardening methods is given in [4, 11].

However, the determination of optimal process parameters for a given load still requires an elaborate experimental set-up and subsequent time-consuming and cost-extensive measurements of the surface layer's state. Previous publications [1, 5, 8] proposed the application of the Finite Element Analysis (FEA) as an effective and cost reducing alternative to an experimental set-up. However, these works were only able to provide a qualitative prediction of the surface layer state due to the simplifications they imposed to the model geometry, boundary conditions and material.

In order to enable the development of FEA-models, which are capable of a quantitative prediction of the surface layer state after roller burnishing, a clear knowledge of the interactions between process parameters, components geometry and their influence on the process results is of eminent importance. This article shows the experimental

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examination of the roller burnishing process and the analysis of the influence of its process parameters and different used geometries of an analogue test specimen on the process results. The experimental results were evaluated and used for the development and verification of the FEA-models described in [7].

2 Experimental details

2.1 Geometry and process description

The test specimen used in the following examinations were extracted from forged and heat treated disks. Their geometries, as shown in Fig. 1, were chosen specifically to represent typical shapes of turbine blade and turbine disk components. A nickel alloy, IN7 18, was chosen, which is commonly used for aero-engines hot section components. The test specimen were solution heat treated at 955°C for one h, subsequently aged at 720°C and held at 620°C for 8 h, in order to resemble a reality-near material state as used for turbine components.

The test specimen surfaces were prepared by grinding. Grinding process parameters were chosen, so that the stress induction in the surface layer was minimised. A surface roughness of $R_a = 0.5 \mu m$ was measured perpendicular to the grinding direction (0°-direction in Fig. 2).

Three different plane geometries (A1, A2, A3) with variable thickness (20, 5, 1 mm) were chosen in order to examine the influence of thickness on the surface layer state. The influence of different geometry shapes is considered by the radii R1 and R2 with respectively 1 and 2 mm radius, as well as by the drilling holes B1 and B2 with 13 and 6.5 mm diameter, respectively.

For all geometries the same roller burnishing strategy was applied. The processed surfaces were roller burnished using a meander path.

The process parameters are presented in the following sections for each roller burnishing process. In order to

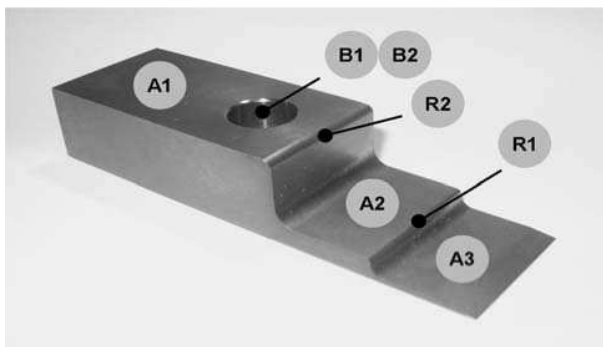
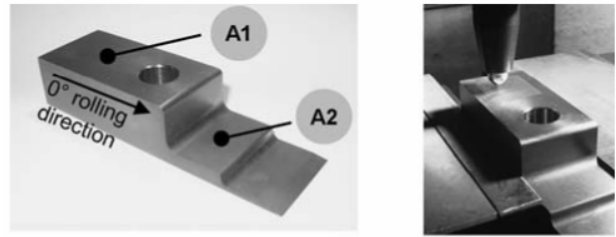


Fig. 1 Test specimen geometries and surface markings



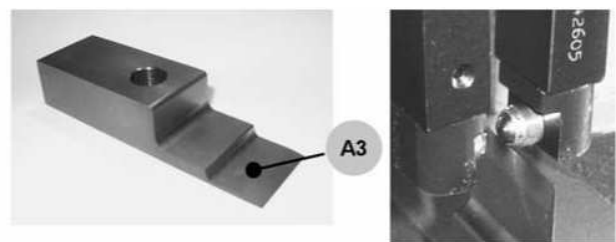
ball diameter BD	rolling pressure RP	rolling direction RD	coverage / overlap CO
mm	bar	degree	%
3	50	0	30
6	150	90	60
13	250		80

reference parameters

Fig. 2 Process parameters for roller burnishing on the plane geometries A1 and A2

analyse the correlation between process parameters and process results a full factorial approach was chosen and all parameter combinations were examined using the process parameters listed in Figs. 2, 3 and 4. The highlighted parameters were chosen as reference parameters because they enable an optimal induction of high and deeply reaching stresses and strain hardening as well as good surface quality at short process times.

Previous research results in [8] have shown that feed velocity has no significant influence on the process results. A feed velocity of 10 mm/s was chosen for all experiments. According to these research results thermal effects caused due to roller burnishing also do not influence the surface layer state after the process. Therefore, thermal effects and



ball diameter BD	rolling pressure RP	rolling direction RD	coverage / overlap CO
mm	bar	degree	%
6	50	0	30
	150	90	60
	250		80

reference parameters

Fig. 3 Process parameters for roller burnishing on the thin walled geometry A3

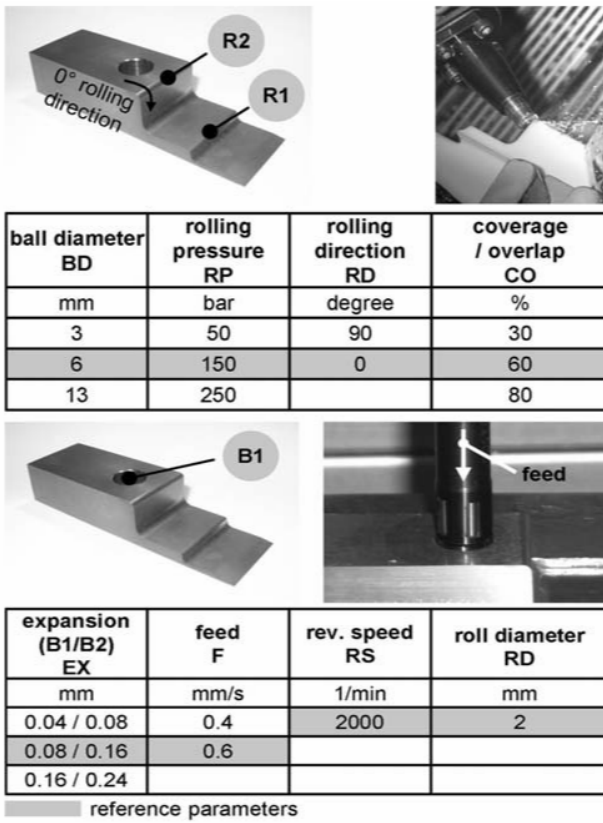


Fig. 4 Process parameters for roller burnishing on the radii R1, R2 and on the drilling holes B1 and B2

the influence of the velocity will be neglected in the following examinations of the roller burnishing process.

2.2 Roller burnishing of plane geometries

The roller burnishing process is performed on the plane geometries A1 and A2 using a hydraulic tool as shown in Fig. 2. The application of hydraulic tools enables the induction of constant pressure on the surface independent of its surface quality or eventual ripple.

2.3 Roller burnishing of thin walled geometries

The roller burnishing of thin walled geometries requires a special tool, which was developed in [8]. The application of common roller burnishing tools is not possible because of the applied pressures and the thereby induced stresses in the surface layer. These near-surface stresses in the surface layer initiate compensative strains further in the test specimen inside, which lead to deformation of the thin walled geometries. In order to prevent this effect and to minimise the induced deformations of the test specimens, a new tool has been developed in [8]. This tool applies forces of same amount but opposite direction to both surfaces of the thin geometry (Fig. 3). By doing this, the above mentioned effect caused by the induced stresses and the thereby

caused compensative strains could be omitted, so that a deformation of the thin walled geometry is minimised.

The process parameters for the roller burnishing of the thin walled geometry A3 are listed in Fig. 3. Since the tool allows only the usage of a rolling ball diameter of 6 mm this process parameter could not be varied.

2.4 Roller burnishing of curved geometries

The roller burnishing of radii has been performed using a 3-axis-milling machine with a rotary table. The rotation of the test specimen was performed by the rotary table and the feed was performed by the machine's spindle, as shown in Fig. 4. Using this experimental set-up, it could be ensured, that the rolling tool is always positioned perpendicular to the radius' surface and that the applied process force is constant at any time.

Drilling holes were roller burnished using a mechanical tool. In order to induce stresses into the surface layer, the plastic deformation of the drilling hole is caused by its expansion. The expansion amount can be determined by adjusting the diameter of the cylindrical rollers. The rollers diameter can be determined by displacement of the axial position of the cone shaft ending.

The process parameters for the roller burnishing of the radii R1 and R2 as well as for the drilling holes B1 and B2 are listed in Fig. 4.

3 Measurement methods

3.1 Hole drilling stress measurement method

For the hole drilling measurements an incremental method was applied, which is commonly used for the determination of in-depth non-uniform residual stress states [3, 6, 9]. In order to calculate the residual stresses corresponding to the measured strain, an in-house developed equipment by MTU was applied, using the integral evaluation method. A Ti-Al-Ni plated tungsten-carbide-driller with a diameter of 0.8 mm was used.

3.2 X-Ray stress measurement method

The X-ray measurements on the test samples were carried out on three different measuring devices at MTU and WZL. Measurements in depth were performed by successive electro polishing. Stress relaxation due to the material removal by electro polishing was not taken into account, since the removed area was small. All X-ray measurements were evaluated by the $\sin^2\psi$ method.

Additional to the X-ray diffraction measurements at the plane surfaces, measurements were carried out on test specimens of IN718 at the concave curved surfaces with a radius of 1 and 2 mm. In order to consider the specification, the beam diameter has to be smaller or equal than one-fifth of the radius measured. Therefore, a beam diameter of 0.2 mm was used.

3.3 Measurement of surface roughness

Useful roughness parameters for the characterisation of the surface topology of roller burnished components are so called amplitude parameters, as they characterise the change of the surface profile in height. For the characterisation of the surface topography of the test samples the roughness parameter Ra was used.

According to DIN EN ISO 4288:1998 the values of Ra are usually averaged over five individual measuring distances. The measuring direction was always perpendicular to the roller burnishing direction.

3.4 Micro hardness measurement method

In order to characterise the work hardening state after roller burnishing micro hardness measurements were carried out using a Fischerscope HCU micro hardness measuring device.

The micro hardness measured was the Vickers hardness. The preparation of the embedded test specimen is shown in Fig. 5. In order to resolve the strong micro hardness gradients in the surface near region, the measurements were performed on a diagonal cut. This enables a higher number of measurements in the surface layer. Finally the real depth of the performed measurements can be calculated by a projection into the plumb line.

The applied test load for the roller burnished test specimens was 500 mN. The loading and unloading time was set to 20 s. For each depth at least three measurements were conducted. The micro hardness values plotted in Chap. 4 of this article are averaged values from these measurements.

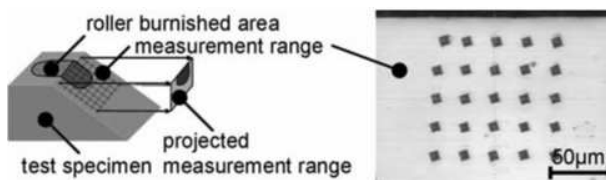


Fig. 5 Micro hardness measurement method

4 Results

In the following sections a description of the measurement results and their correlation with the process parameters will be given. Hereby, the induced residual stresses, the surface roughness and the measured micro hardness will be considered for all previously described roller burnishing processes.

The influence of the process parameters on the measured results is principally the same for the examined plane geometries A 1 and A2. For this reason, in the following sections only the geometry A1 will be considered, whereby the process parameters will be varied.

A direct comparison of the measured results for the variation of the geometry shapes is difficult, since different roller burnishing tools and strategies had to be used. The plane and convex geometries were processed by a hydraulic tool, which ensures a constant pressure application during the roller burnishing process. For the concave geometry elements a mechanical tool was used, since their form and dimension do not allow an application of hydraulic tools. This tool allows the induction of a defined deformation into the surface layer, whereas the thereby applied pressure is unknown. For this reason it has to be considered that the measured stresses for this process type are not directly comparable with the hydraulic processes.

4.1 Comparison of the stress measurement methods

The characterisation of the surface layer's residual stress state can be provided using both previously described measurement techniques: the hole drilling and the X-ray method. Since the measurement of residual stresses using the hole drilling method requires less time and costs, this method is to be favoured. However, compared to the X-ray method, the hole drilling method shows some disadvantages, which have to be taken in account:

- Higher errors for measurement of high stress gradients
- Error of measurement results increases in the surface near region
- Non-consideration of process-related plastic strain

The applicability of the hole drilling method for the characterisation of the surface layer's state after roller burnishing was examined by comparison of measurements performed with this method and measurements by the X-ray method on the same roller burnished test specimen.

In order to reduce the time and cost factors of the X-ray measurements the accuracy of the hole drilling results was examined on three significant depths:

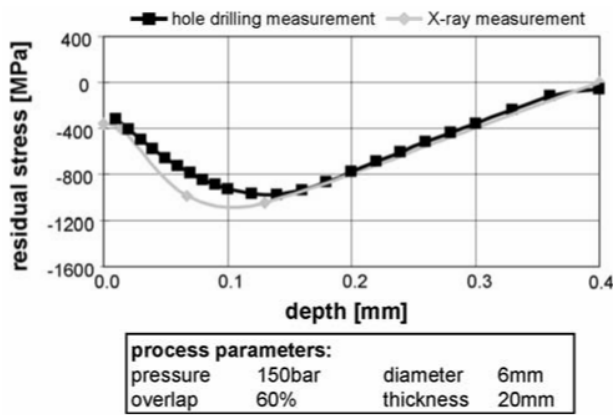


Fig. 6 Comparison between hole drilling and X-ray residual stress measurements (in parallel direction)

- Directly on the surface
- In the depth, where maximal residual stresses were measured by the hole drilling method
- In the depth, where the residual stresses were measured as zero

Figure 6 shows a result comparison of both methods. The good correlation of the X-ray and hole drilling measurement results lead to the conclusion that the deep reaching residual stresses and their low gradients enable the application of the hole drilling measurement method for the determination of the residual stresses in the surface layer for the roller burnishing process.

4.2 Influence of the overlap

The residual stress development for the overlap variation is shown in Fig. 7. These process parameters have no significant influence on the residual stress state.

Roughness measurement results in Fig. 7 show a significant influence of the overlap. Very good surface roughness quality can be achieved by increasing the overlap. However, it has to be considered that this parameter determines the process time and that high overlap requires long process times. Therefore, an overlap of 60% is recommendable, since it allows the induction of high residual stresses and good surface roughness at short process times.

4.3 Influence of the rolling pressure

The influence of the rolling pressure on the residual stresses is shown in Fig. 8. An increase of the rolling pressure causes a significant increase of the maximal induced residual stresses and the depth they can reach. However, a saturation of the achievable increase could be observed for the examined material at 150 bar, so that the increase of the residual stresses between 150 and 250 bar is minimal.

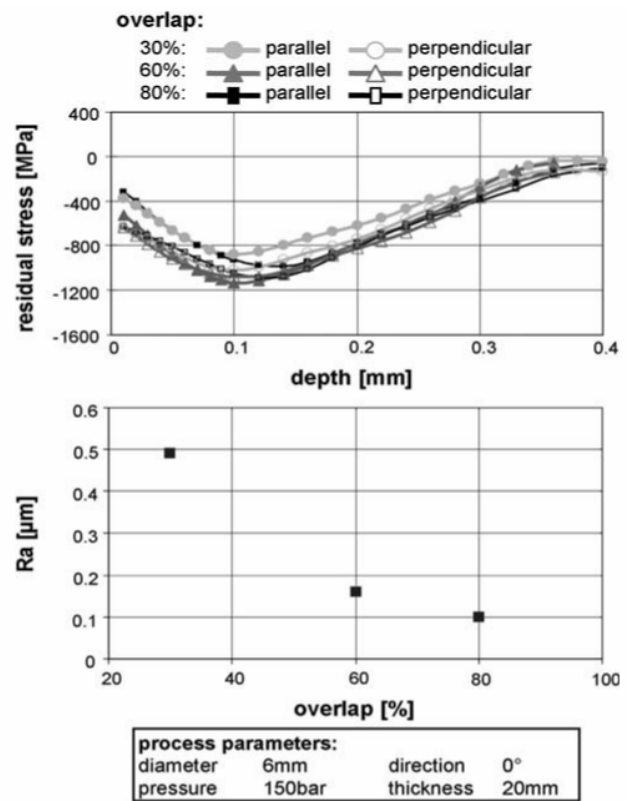


Fig. 7 Influence of the overlap on residual stresses and surface roughness

The development of the residual stresses in dependence of the rolling pressure can be also observed on the strain hardening. As shown in Fig. 8, the induced hardening can be compared qualitatively to hardness increase due to the roller burnishing process. The depth of maximal hardness coincides with the depth of the stresses.

Measurements of the surface roughness for different rolling pressures show no significant change of the results. Therefore, it can be concluded that the surface roughness is not influenced by the applied rolling pressures (Fig. 8).

It can be concluded that a rolling pressure of 150 bar is sufficient for the induction of high residual stresses and strain hardening. Furthermore, using this pressure the risk of damaging the processed surface can be reduced.

4.4 Influence of the rolling ball diameter

In order to examine the influence of the roller ball diameter on the surface layer state after roller burnishing, three different diameters were chosen: 3, 6 and 13 mm.

In Fig. 9 the influence of this variation on the residual stress state is shown for IN718. An increase of the rolling ball diameter leads only to a slight increase of the residual stress amplitude and to significant increase of the maximal

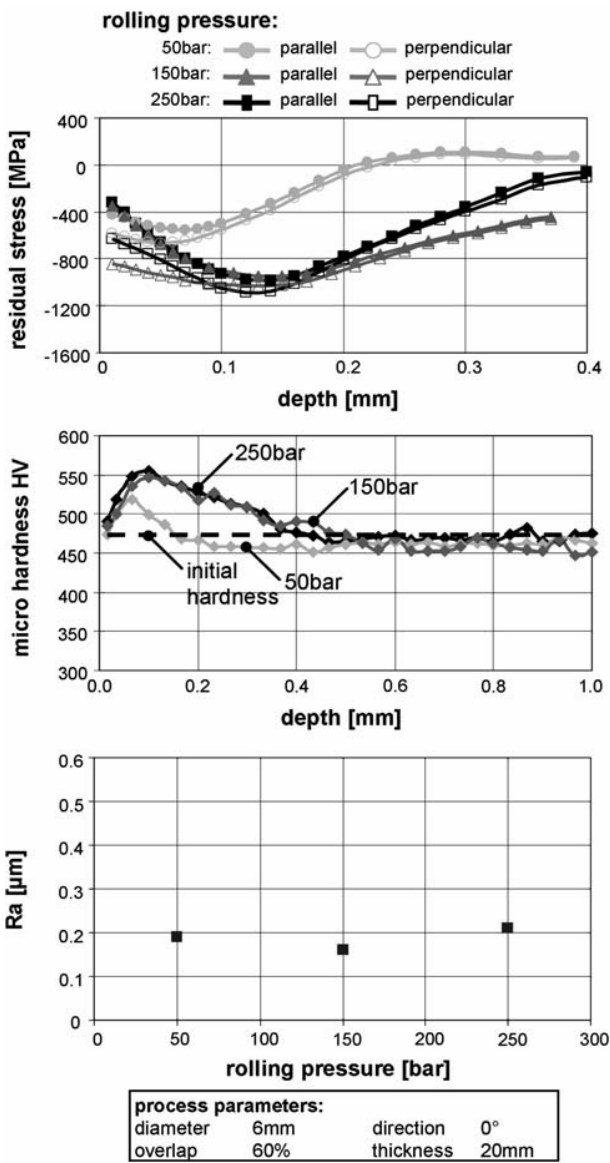


Fig. 8 Influence of the rolling pressure on residual stresses and surface roughness

stress depth. Regarding this depth, saturation towards higher rolling ball diameters could be observed.

The influence of the rolling ball diameter on the surface roughness is shown in Fig. 9. For small roller ball diameters the surface roughness improves, which can be explained by the smaller width of the contact surface. This reduces the lateral elevation caused during the roller burnishing process considerably due to the decrease of the simultaneously formed volume at every time increment.

Therefore, the choice of a rolling ball diameter of 6 mm is recommended, since it allows the induction of high and deep reaching residual stresses without causing higher surface roughness.

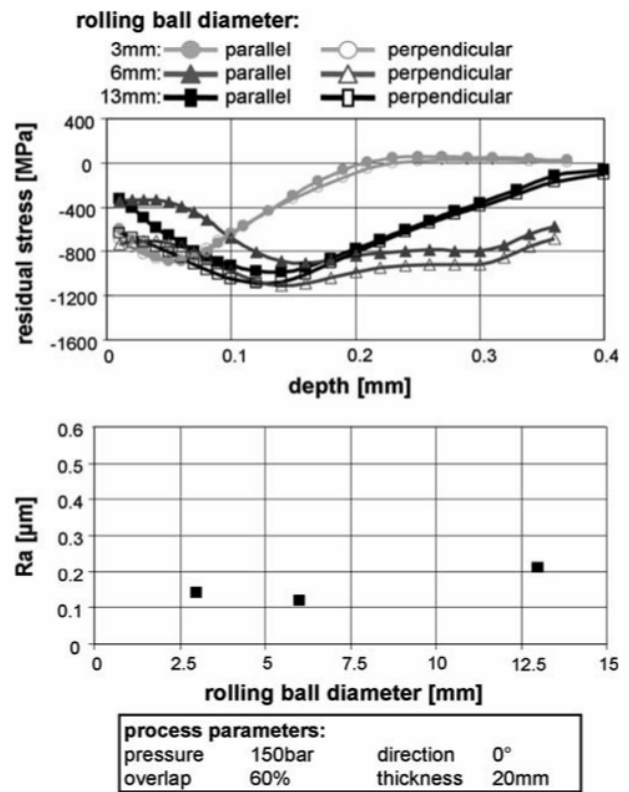


Fig. 9 Influence of the rolling ball diameter on residual stresses and surface roughness

4.5 Influence of the thickness

The influence of the thickness on the measured process results was examined using three different plane geometries with 1, 5 and 20 mm thickness.

The thickness of the examined test specimen does not influence the surface roughness significantly, as shown in Fig. 10. For this reason it can be assumed that the surface roughness is constant for the examined thickness variations.

The measured residual stress distributions are shown in Fig. 10. These measurements show that the variation of thickness influences above all the near-surface residual stresses. With decreasing thickness, the residual stresses on the surface change from compressive to tensile stresses. Such tensile stresses on the surface can negatively influence the fatigue strength of the roller burnished components. For this reason this effect has to be omitted by choosing suitable process parameters.

In order to determine such parameters, the rolling pressure was varied for the thin walled geometry, since this parameter was determined as a major influence on the residual stresses.

In Fig. 11 the results of this examination show that a decreasing rolling pressure leads to compressive residual

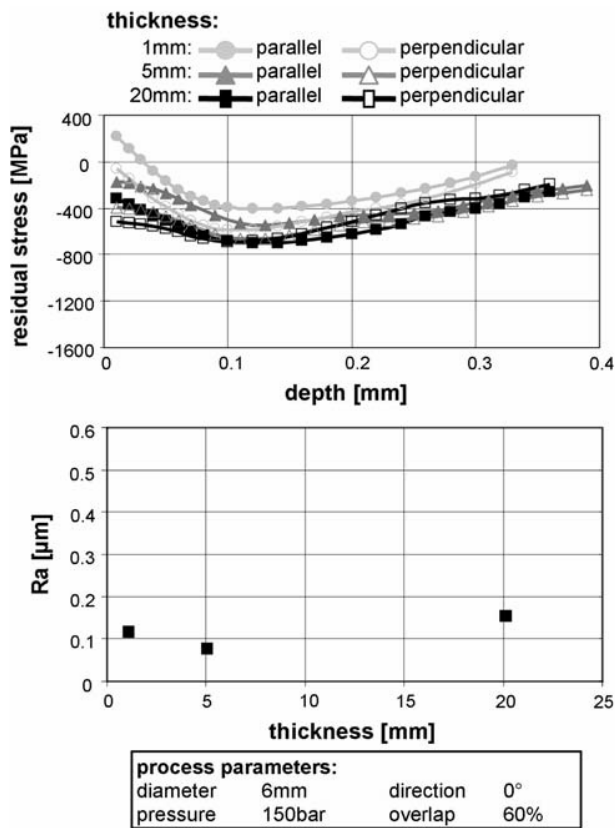


Fig. 10 Influence of the test specimen's thickness on residual stresses and surface roughness

stresses on the surface. The depth of the maximal stresses is comparable to the stresses obtained by the application of higher rolling pressures. However, for rolling pressure of 50 bar compressive residual stresses do not reach the same depth as higher pressures.

In summary, it can be stated that thin walled geometries require lower stresses in order to prevent tensile stresses on the surface. Therefore, for this geometry a rolling pressure of 50 bar is recommended.

A comparison of the residual stresses for a thickness of 20 mm in Fig. 8 and for 1 mm in Fig. 11 shows similar results for low roller burnishing pressures. However, the influence of the thickness becomes more important with higher rolling pressure and the amount of tensile residual stresses in the surface-near area increases. This effect can be explained by considering that the residual stresses within the test specimen have to be in equilibrium. The compressive residual stresses induced by the roller burnishing process have to cause compensation stresses. For a thick walled test specimen these compensation stresses can spread over a large domain and do not influence the residual stresses in the surface layer. For thin walled geometries the induced compressive stresses on both sides of the test specimen cause compensation stresses, which

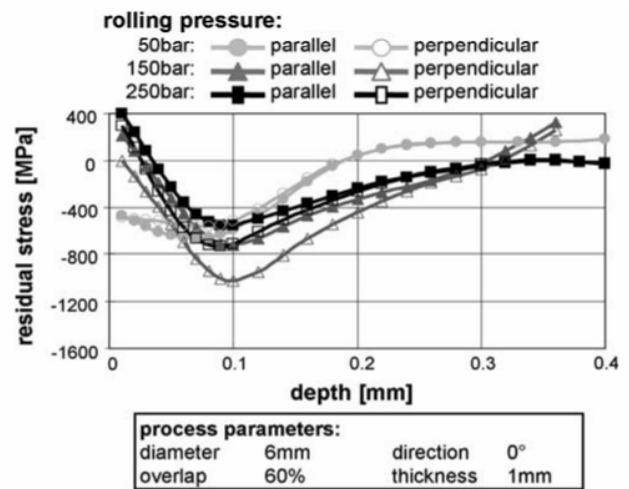


Fig. 11 Influence of the rolling pressure on residual stresses for the thin walled geometry

influence each other. For high rolling pressures this can result in tensile stresses in the surface-near area. Finite Element Analysis of the roller burnishing process, described and verified in [7], shows this effect (Fig. 12).

4.6 Influence of the

The influence of the test specimen geometry on the process results was examined by variation of the geometry form. A

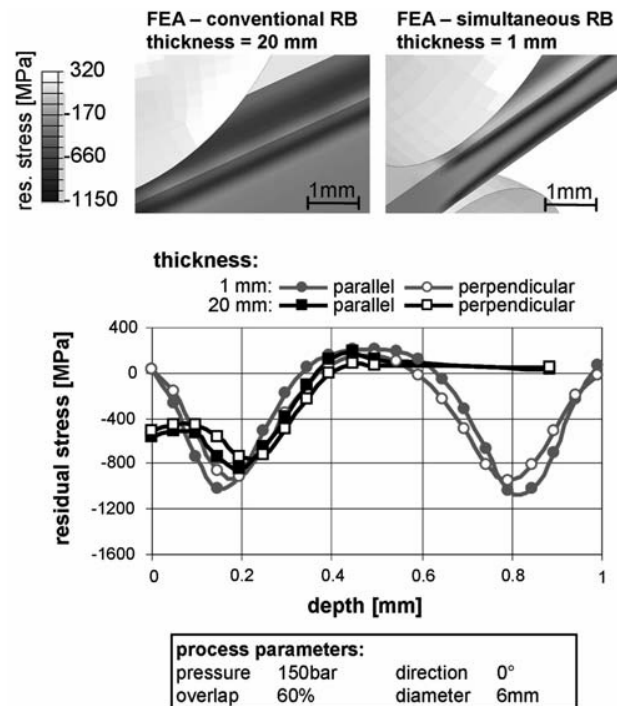


Fig. 12 FEA and residual stress state of conventional and simultaneous roller burnishing

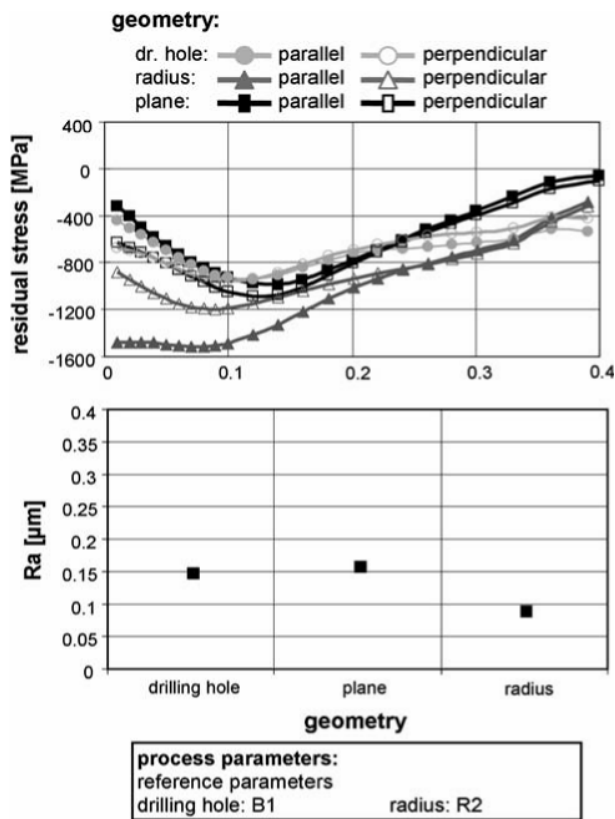


Fig. 13 Influence of the geometry on residual stresses and surface roughness

plane geometry was chosen as reference. Additionally two convex geometries were processed (R1 and R2-radii) as well as two concave geometries (drilling holes with $\varnothing 6.5$ and $\varnothing 13$ mm).

The measured residual stress distributions in Fig. 13 show similar stress gradients in the test specimen depth. The comparison between the plane and convex geometries shows further that due to the changed contact situation between two curved surfaces higher and deeper reaching stresses could be induced on the surface.

In Fig. 13 a comparison of the measured surface roughness Ra for these three geometries shows that all processes could provide almost the same low roughness. Therefore, it can be concluded that the geometry has no significant influence on the surface roughness.

5 Conclusion

The durability and reliability of highly stressed turbine components can be increased by hardening of the surface layer, which can be achieved by roller burnishing. In order to develop well funded process knowledge about the correlation of the process parameters, the processed geometry

and the surface layer, experimental trials were performed on different geometries of an analogue test specimen with varying process parameters.

The measurement results show that above all the rolling pressure influences the amount and depth of induced residual stresses and strain hardening. The surface roughness is mainly influenced by the overlap. An additional influence on the surface roughness could be observed for high roller ball diameters, which can cause an increase of the roughness due to higher lateral formed material elevation.

The test specimen thickness influences mainly the near-surface residual stresses. The choice of suitable process parameters for thin walled geometries is very important, because otherwise tensile residual stresses can be induced, which can lead to a reduction of the component's fatigue strength.

Finally, the examination of the geometry influence on the residual stresses show that the contact area determines the amplitude and depth of the induced stresses.

Using the examinations described in this article a clear knowledge of the correlation between process and geometry parameters could be developed. This knowledge can be used for the determination of adequate process parameters for a given task. Furthermore, it enables the development and validation of FEA-models, which can substitute time-consuming and cost-intensive experimental examinations.

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