Effects of an innovative deep rolling process on the subsurface properties of thin-walled components

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Introduction

In aerospace industry, the need for components with high fatigue life is increasing steadily. In particular, aircraft engines have to withstand high aerodynamic, mechanical and thermal loads during operation. The most common defect of compressor blades is caused by impact damage of small foreign objects. Out of such damage, vibration cracks during operation arise and cause safety-critical blade loss. Consequently, the fatigue life of such components is reduced [1]. By mechanical work hardening of the subsurface area compressive residual stresses can be induced, which has a positive impact on the fatigue life of these components [2-5]. Currently the residual stress state of compressor blades is optimized by shot peening. This procedure allows the processing of complex geometries and undercuts. A major drawback of this process is the high surface roughness which has a lasting influence on the flow characteristics. Furthermore, an additional process step in order to increase surface quality is required. An alternative process to induce residual stresses is deep rolling whereby these disadvantages are avoided. At present, it is not possible to influence the subsurface properties of thin-walled components by deep rolling due to shape deviations of the component after machining. Moreover, currently no deep rolling tool exists which allows the machining of complex geometries and undercuts. A further disadvantage is the application of fluid medium in order to build up the rolling pressure which leads to a high leakage flow affecting the environment.

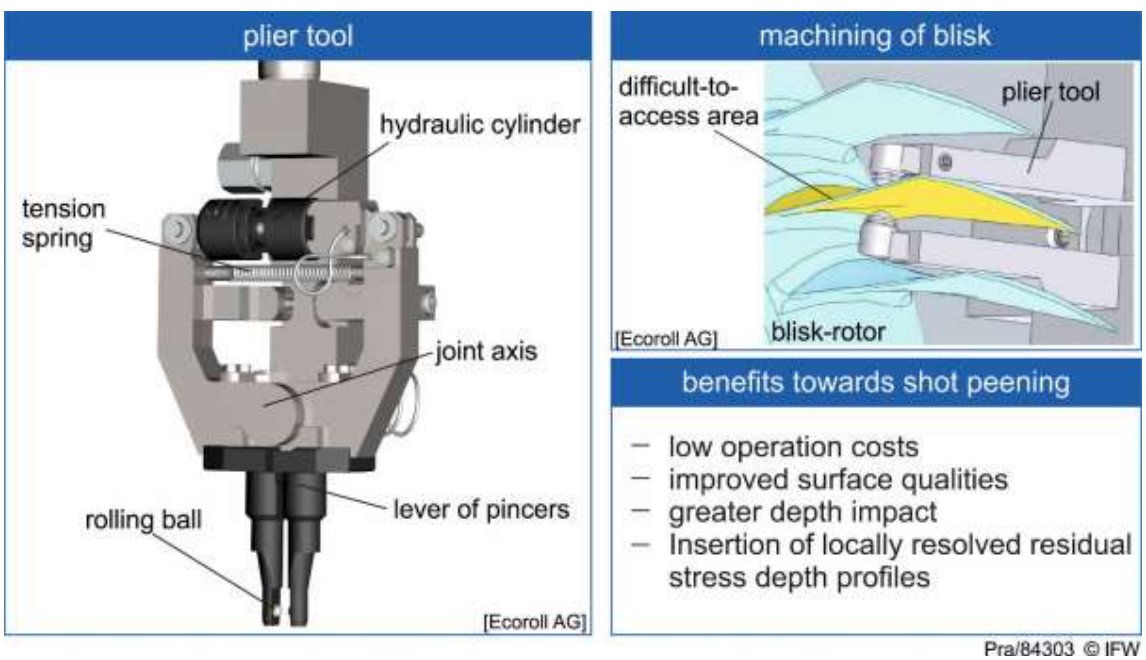


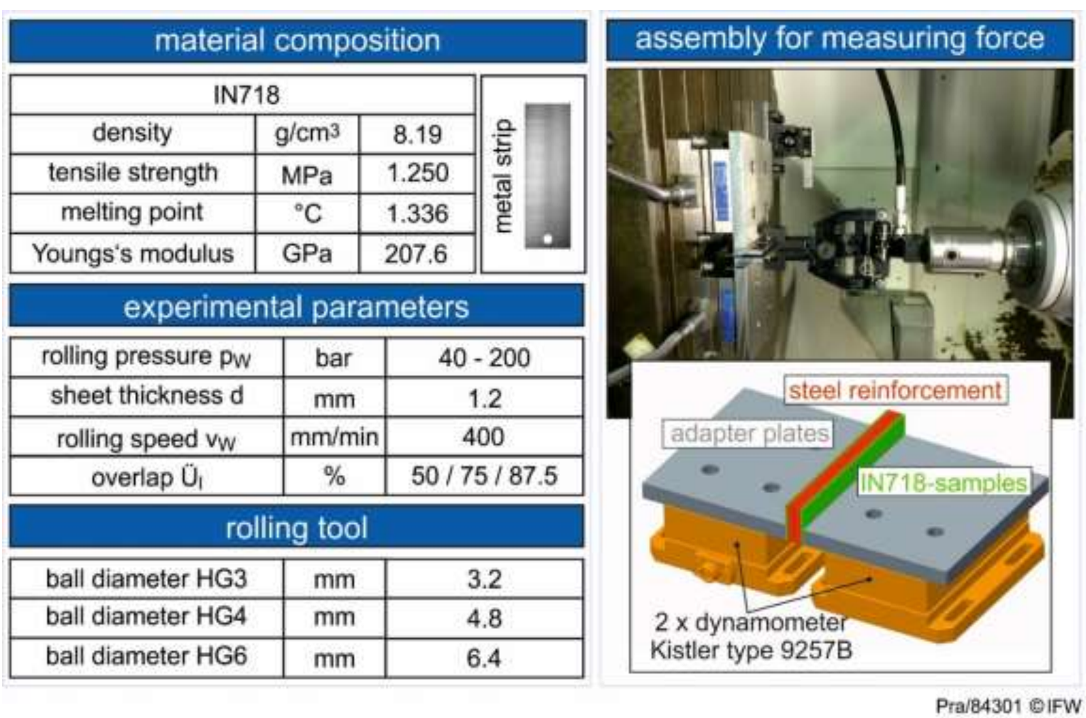
Fig. 1: Innovative pincer rolling tool

Within the framework of a research project, an innovative plier tool was developed which allows the machining of thin-walled, complex geometries by means of deep rolling for the first time. It consists of two plier arms, which machine thin components simultaneously from both sides (Fig.

1). In this case, the forces are applied perpendicular to the surface and thereby prevent plastic deformation by equilibrium of forces. Through locally resolved pressure control so far non-controllable shape deviations in area of thin walls can be avoided. Furthermore, a pressure regulation enables the induction of defined residual stress depth profiles. The lever of the pliers with the rolling ball size can be changed in order to investigate the influence on the residual stress depth profile. By a mechanical movement of the hydraulic cylinder the levers of the plier are pressed together. By an innovative aerosol pressure system high leakages of rolling oil are reduced.

Objectives
The aim of this study is to investigate the performance properties of this innovative deep rolling plier tool in order to influence the subsurface properties of compressor blades. Furthermore, the results are used to generate an empiric model for the prediction of residual stress depth profiles. Hereby a defined residual stress depth profile shall be induced in a compressor blade.

Methodology
The rolling process used in this study is based on the local adjustment of the rolling pressure. Therefore, it must first be determined how quickly the pressure can be regulated. For this, the response times from the control valve to the processing point are needed. Thus in the study presented here, first of all the response capacity of the locally resolved pressure regulation depending on the rolling speed is examined. The rolling speed with satisfying accordance between set and actual rolling pressure is used for further investigations. In the next step, the influence of different sheet thickness of the studied material IN718 on the rolling forces is analyzed. The results of these preliminary tests show that the limit of the rolling speed is set at 400 mm/min, and the sheet thickness has no influence on the residual stress depth profiles [5]. Henceforth, only 1.2 mm sheet thickness is considered in the following investigations. Moreover, the shape deviations were measured before and after deep rolling in order to evaluate the new plier tool.



material composition

IN718		
density	g/cm3	8.19
tensile strength	MPa	1.250
melting point	°C	1.336
Youngs's modulus	GPa	207.6

experimental parameters

rolling pressure p_W	bar	40 - 200
sheet thickness d	mm	1.2
rolling speed v_W	mm/min	400
overlap $Ü_l$	%	50 / 75 / 87.5

rolling tool

ball diameter HG3	mm	3.2
ball diameter HG4	mm	4.8
ball diameter HG6	mm	6.4

Fig. 2: material characterization and experimental procedure

Finally, the effects of the process parameters rolling pressure, overlap of rolling, and rolling ball diameter on the residual stress depth profile were analyzed in rolling and transverse direction. For this purpose, the experimental parameters and experimental setup shown in Fig. 2 were used.

For the determination of the residual stress depth profiles, the angle dispersive X-ray diffraction using the $\sin^2\psi$-method is applied. Co Kα radiation was used for X-ray stress analyses on {311}-lattice planes at $2\theta_0$=111.1°. The calculated X-ray elastic constants used were $E^{\{311\}}$=203 GPa and $\nu^{\{311\}}$=0.32. Residual stress depth profiles were recorded by stepwise electrolytical removal of materials layers. The redistribution of residual stresses due to layer removal was corrected by mechanical equilibrium considerations following the method of Moore and Evans.
On the basis of the analysis of the results of these measurements, an empirical model for the prediction of compressive residual stresses is developed. Furthermore, this model is used to derive user recommendation for machining a blade integrated disk (blisk). The model is validated by comparison of the target residual stress depth profile with the actual profile.

Results and analysis
The results of residual stress measurement show higher compressive residual stresses in transverse than in rolling direction. This direction corresponds with the radial direction of the blade / blisk which is the direction of maximum loading stress. For this reason, the residual stress effect on a possible foreign object damage is ideal. With the aim to produce maximum compressive residual stresses in the loading stress direction of the component, in further investigation only residual stresses in transverse direction are considered. The overlap describes the relative superposition of a previously applied rolling path by a subsequently produced rolling path. As a result, the process time increases with increasing overlap since the infeed is reduced. An increase of the overlap from 50 % to 75% leads to higher compressive residual stresses. A further increase in the overlap does not result in any change regarding the maximum compressive residual stresses. Considering the productivity of the deep rolling process for further investigations, the overlap was fixed to 75 % because an overlap of 87.5 % would double the processing time. With these configurations, a satisfactory compromise between large induced residual stresses and process time is achieved.

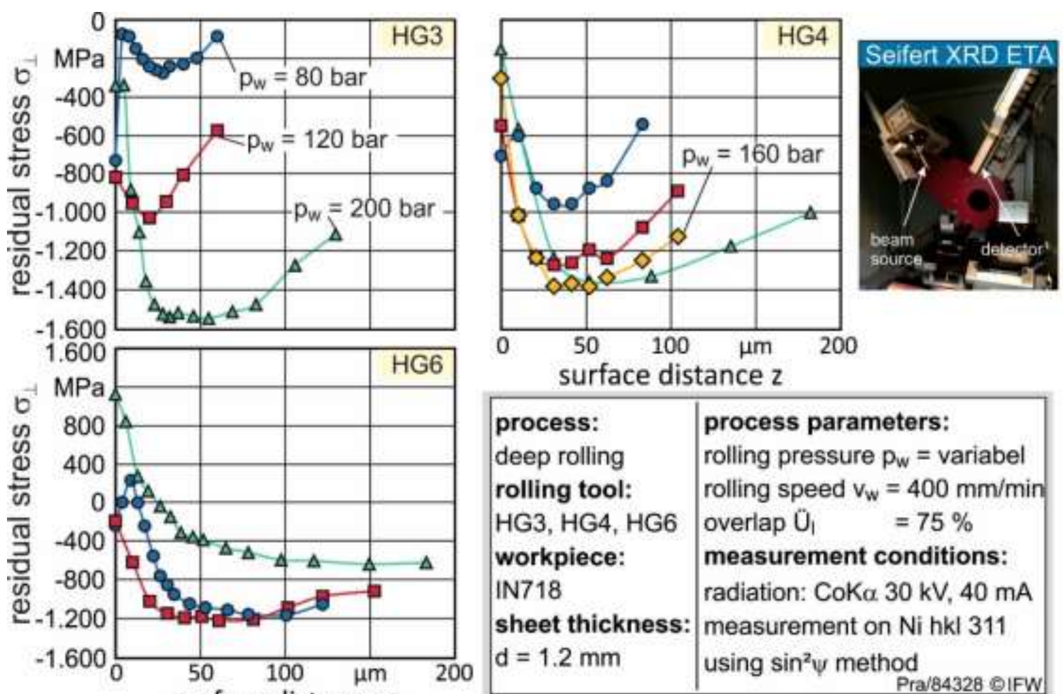


Fig. 3: Influence of rolling pressure and ball diameter on residual stress depth profile

The significant parameters which influence the residual stress depth profile are the rolling pressure and the rolling ball diameter (Fig. 3). The maximum of compressive residual stresses are located beneath the surface and shift to greater depth with increasing rolling pressure and ball diameter. This effect results on one hand from increasing Hertzian pressure with increasing rolling pressure and on the other hand from the plastic deformation generated by a higher contact surface between rolling ball and workpiece by increasing the ball diameter.

With the analysis of the present results, a linear regression model for the prediction of residual stresses was derived as shown in Eq.1 to Eq.3. Three significant points of the residual stress depth profile are used for the model construction. These are the residual stress at the surface $\sigma_{\perp,z=0}$, the maximum residual stress $\sigma_{\perp,max}$ and the depth of the maximum residual stress z_{max}.

$$\sigma_{\perp,z=0} = 383 \cdot d_W + 433.5 \cdot p_W - 287.556 \qquad \text{(Eq. 1)}$$

$$\sigma_{\perp,max} = 193.7 \cdot d_W^2 + 225.7 \cdot p_W^2 + 427.5 \cdot d_W \cdot p_W - 202.3 \cdot d_W - 16 \cdot p_W - 1318.4 \qquad \text{(Eq. 2)}$$

$$z_{max} = 22.8 \cdot d_W \cdot p_W - 18.2 \cdot d_W - 29.8 \cdot p_W - 52.1 \qquad \text{(Eq. 3)}$$

The coefficient of determination R^2 indicates the compliance between the simulated and experimentally determined values (Fig. 4). Significant parameters of the model are both the rolling pressure p_W and the ball diameter d_W as well as the interaction of these two variables.

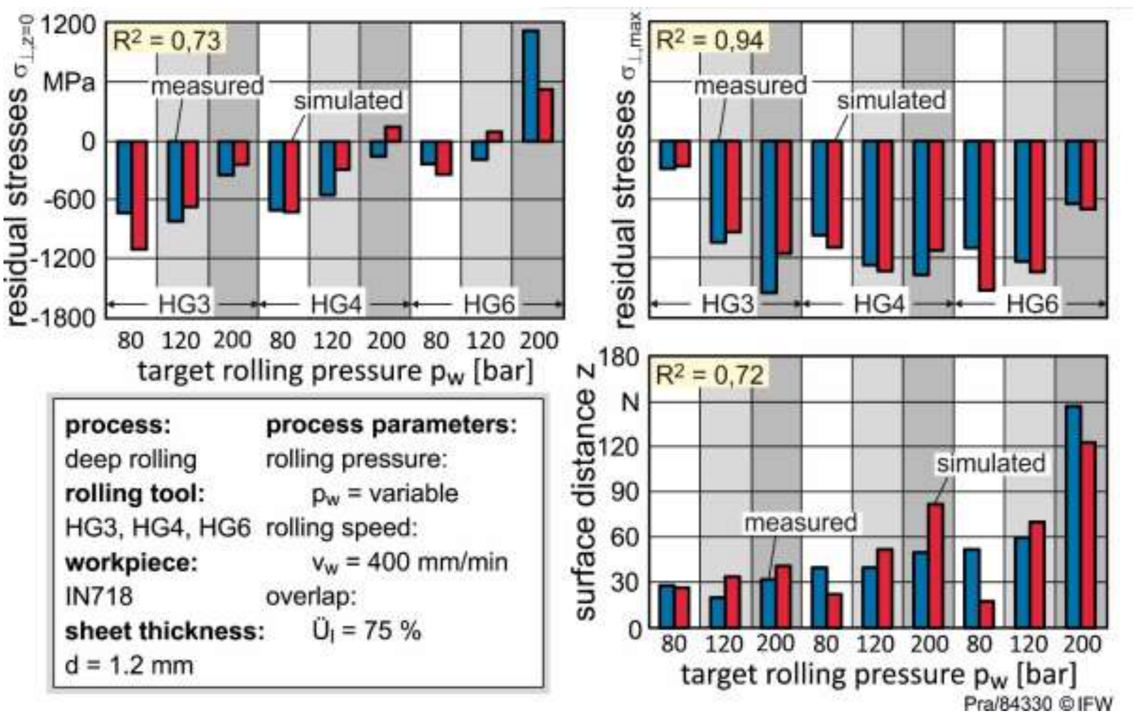


Fig. 4: Comparison of regression model and experimental results

With the aid of this model the process parameters for a target profile in a compressor blade can be predicted. Due to similar mechanical materials properties, a transferability of the model, which was constructed for IN718, to titanium is assumed. The comparison of the target and the actual profile leads to satisfactory compliance of the predicted tendencies (Fig. 5). Furthermore, optical measurements before and after the rolling process have shown that shape deviations can be avoided by this innovative deep rolling process with a plier tool.

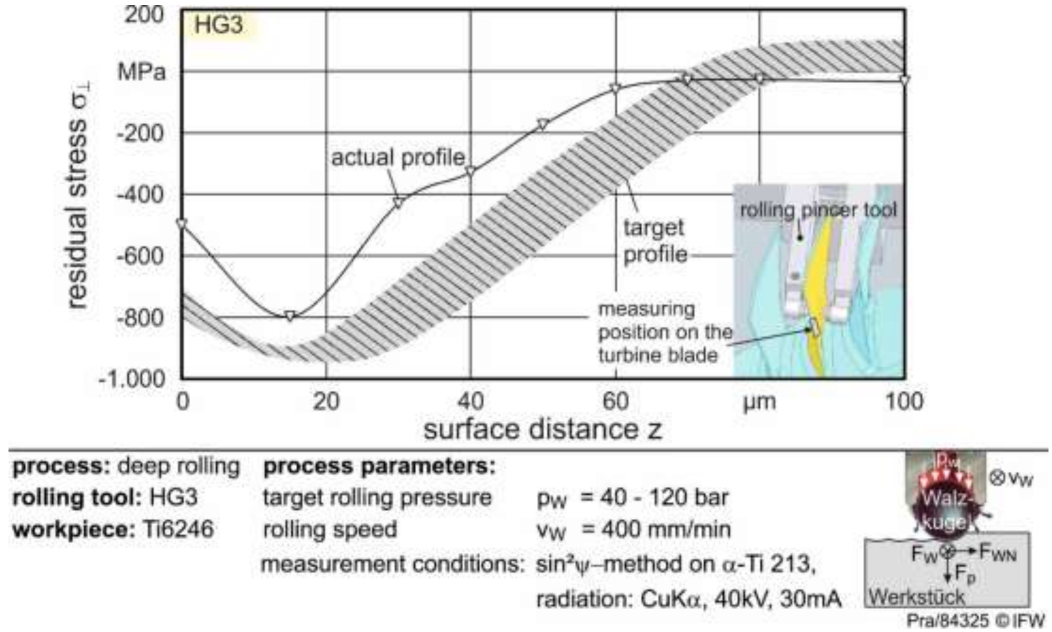


Fig. 5: Comparison of target and actual residual stress profile of a deep rolled compressor blade

Conclusions

In conclusion, an innovative plier rolling tool has been developed for the machining of thin-walled components. The operating characteristics of this new tool were investigated in this work. The experimental investigations show that the rolling pressure and the rolling ball diameter influence the subsurface properties significantly. With the experimentally determined residual stress depth profiles an empiric model was derived in order to deduce a user recommendation for the machining of a compressor blade. The comparison between target and actual depth profile of residual stress shows the potential and the efficiency of this innovative technology.

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