DEEP ROLLING OF TITANIUM RODS FOR APPLICATION IN TOTAL HIP ARTHROPLASTY

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Abstract

Compressive residual stresses are commonly introduced into the near-surface regions of morse taper junctions of modular hip endoprostheses in order to reduce the sensitivity to effects of corrosion, fretting fatigue, and fatigue.
The aim of this study is to evaluate the effects of deep rolling rods of titanium alloy TiAl6Nb7 and evaluate the resulting surface characteristics in comparison with those obtained by commonly applied shot peening procedures.
For this purpose, TiAl6Nb7 rods with a diameter of 15 mm were deep rolled with balls of different diameters and different rolling parameters. The resulting surface topography and residual contamination was analyzed using a field emission scanning electron microscope. The near-surface residual stress states after deep rolling were characterized by means of X-ray diffraction. The findings are discussed with respect to application of deep rolling as finishing process of morse taper junctions of modular hip endoprostheses.

Introduction

The advatages and disadvantages of modular hip endoprostheses with morse taper junctions is are described, and the relevant state of the knowledge is elaborated in [1]. Modular prostheses offer advantages concering the flexibility of reacting on individual geometrical conditions with a relatively small set of different components. They also facilitate individual positioning during implantation. On the other hand, due to the additional interface at the morse taper, additional aspects must be considered for a successful application. The surface of the components must be free of contaminations resulting from the preceeding manufacturing processes. Ferrous contaminations due to shot peening could enhance corrosion. Contamination with abrasive particles of glass or zirconia due to shot peening / blasting operations promote fretting fatigue and reduce the biocompatibility of the implant by the presence of particles as well as of the created corrosion products.
The loading of hip endoprostheses in service life is predominated by bending loads creating tensile loading stresses in the respective areas. These tensile stresses superimpose with those resulting from the pressure at the edge of the morse taper and can cause development and propagation of fatigue cracks, enhanced by stress corrosion cracking due to the biological fluids. Moroeover, relative movements at the interface can occur due to bending load which can lead to fretting corrosion products. The described facts lead to the conclusion that several requirements have to be fulfilled in order to successfully use modular hip endoprostheses with morse taper

junctions. The surfaces must be free of any corrosive or abrasive particle contamination. The interface surface of the morse taper should be smooth and show only small roughness. Finally, in oder to reduce effects of fretting corrosion and/or stress corrosion cracking, the near surface regions should contain compressive residual stresses. Since bending load and edge pressure effects occur, the compressive residual stress states should extend to a decent depth in order to prevent development and propagation of fatigue cracks in subsurface areas with tensile loading stresses.

For the named reasons, deep rolling seems to be an appropriate process for surface finishing of morse tapers. They are always rotationally symmetrical. Deep rolling creates a smooth surface, and residual stress states can be expected to reach to larger depths than shot peening residual stresses. Therefore, the aim of this work was to investigate rods of a titanium alloy after different deep rolling treatments with respect to possible surface contaminations and to the resulting residual stress states.

Material Investigated and Experimental Details

Rods of TiAl6Nb7 with diamteters of 15 mm have been deep rolled with different parameters at a rotational speed of 730 min^{-1}. One sample rod is exemplarily shown in fig. 1. The roughness of the surfaces was about $R_z = 14$ µm. The deep rolling parameters are listed in tab. 1.

After deep rolling, the surfaces of the samples were investigated with a field emission scanning electron microscope (LEO 1525 Gemini) to analyze possible residual particle contaminations.

X-ray residual stress analyses were carried out with an X-ray diffractometer XRD 3000 PTS. The measurements were performed with Cu Kα-radiation on {213}-lattice planes of the hexagonal α-phase of the alloy at the stress-free bragg angle $2\theta_0$=141.05°. Lattice strains were measured at 11 positions in the angular range of $-50° \leq \psi \leq 50°$. Residual stresses were determined in both longitudinal and circumferential direction of the rods according to the $\sin^2\psi$-method [2] using the X-ray values of the elastic constants $E^{\{213\}}$=113 GPa and $\nu^{\{213\}}$=0.32 (for details see [3], e.g.).

The evolutions of residual stresses with depth were determined by stepwise electrochemical removal of surface layers and subsequent X-ray residual stress determinations. A correction of the residual stress values with respect to redistribution of residual stresses due to removal of residually stressed material was not necessary since the remaining cross section of the samples was sufficiently large compared to the cross sections of the removed surface layers.

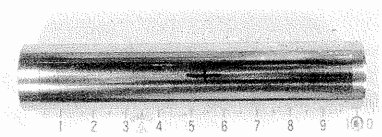

Figure 1: TiAl6Nb7 rods under investigation.

sample no.	cross feed [mm/rev.]	ball diameter [mm]	pressure [bar]	roughness R_z [µm]
1	0.2	6	50	7.5
2			100	3.7
3			150	2.3
4			200	1.7
5			250	1.3
6			300	1.2
7	0.1			0.4
8	0.2	4		1.9
9		13		0.4
10	0.3			1.0

Table 1: Samples investigated with deep rolling parameters and resulting surface roughnesses.

Results and Discussion

The results of the SEM and EDX analyses of the sample surface gave no hints for surface contamination by particles or abrasion products.

The results of surface roughness measurements are listed in tab. 1. Samples 1 to 6 show a continuous decrease of the surface roughness with increasing rolling pressure. The smoothing effect is even more pronounced, if the cross feed is reduced (s. sample no. 7). If samples 6, 8, and 9 are compared, it is seen that increasing ball diameter reduces the surface roughness, if the other parameters are kept constant. Comparing samples 9 and 10 confirms that reducing the cross feed significantly reduces the surface roughness.

Due to the cross feed movement, it cannot be assumed that the resulting residual stress states are symmetrical in a manner that their principal axes coincide with longitudinal and circumferential direction of the samples. Therefore, samples 4 to 6 and 10 were selected for additional residual stress analyses at the surfaces in a direction under 45° between longitudinal and circumferential direction. From these values, the orientation φ of the principal stress axes was calculated using the relation

$$\tan\varphi = \frac{2\sigma_{12}}{\sigma_{ax} - \sigma_{tan}} \qquad (1)$$

with

$$\sigma_{12} = \sigma(45°) - \frac{1}{2}(\sigma_{ax} + \sigma_{tan}). \qquad (2)$$

It turned out that in all of the cases the principal stress directions differed less than ±15° from the longitudinal and circumferential direction, respectively. Therefore, the measuring directions can be considered as principal stress directions.

The results of the residual stress analyses are shown in fig. 2. The upper viewgraph compares the residual stress states of samples 1 to 6, the lower viewgraph compares the residual stress states of the samples 6 to 10 as a function of the distance from the surface.

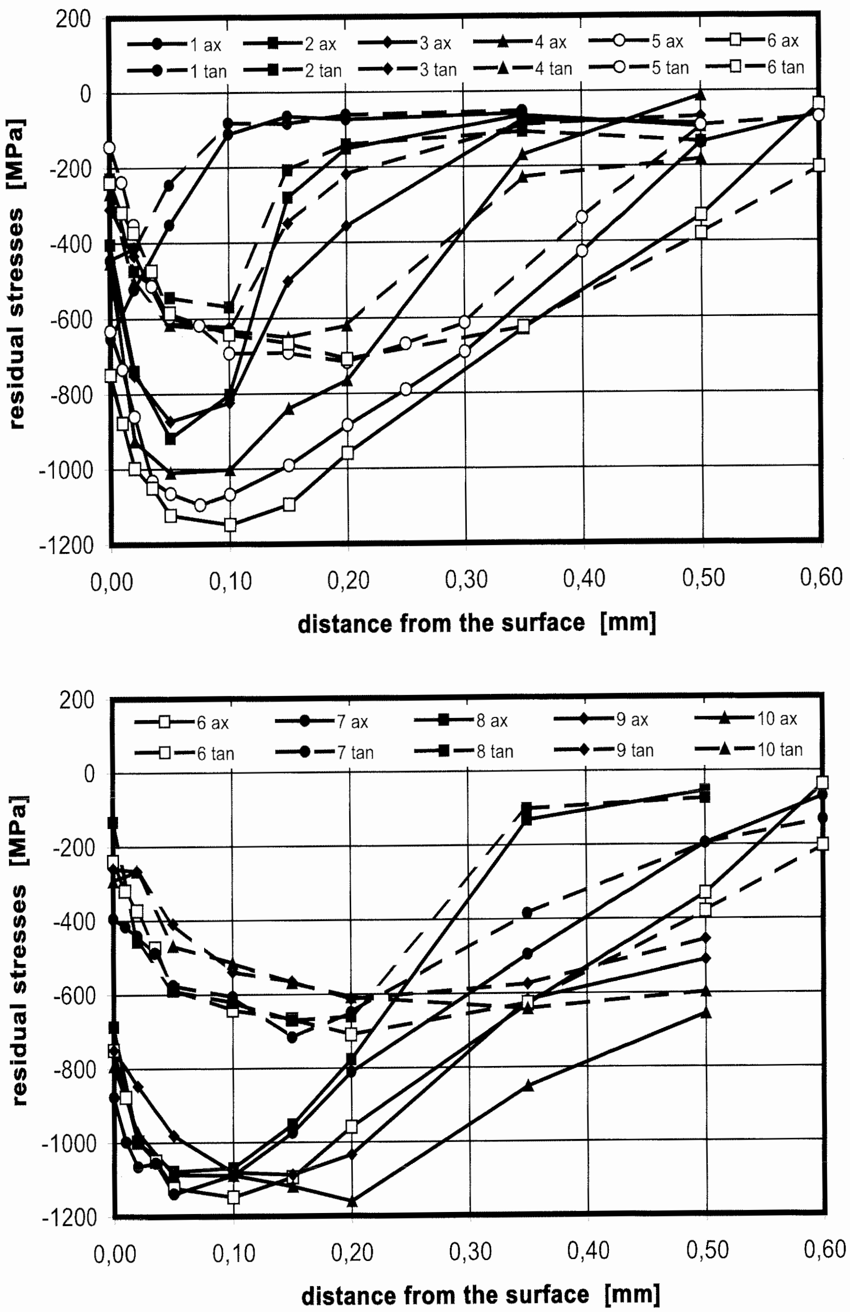

Figure 2: Residual stresses in longitudinal (ax) and circumferential direction of the rods (tan) of the samples 1 to 6 (top) and 6 to 10 (bottom) after deep rolling with the parameters given in tab. 1 and plotted as function of the distance from the surface.

The viewgraphs show typical deep rolling residual stress states with compressive residual stresses and subsurface compressive residual stress maxima. The residual stress values in longitudinal direction (full lines) appear in all cases to be in the range of about twice the residual stress values in circumferential direction (dashed lines). For distances larger than about 0.3 mm from the surface, the differences between longitudinal and circumferential residual stresses become smaller or disappear.

Comparing samples 1 to 6 (upper viewgraph), the effect of increasing rolling pressure is shown with constant ball diameter of 6 mm and cross feed of 0.2 mm/rev. It is found that the low rolling pressure of 50 bar does not create a subsurface residual stress maximum. The maximum of about –650 MPa in longitudinal direction is located at the surface. With increasing rolling pressure, the residual stress maximum increases and moves to larger distances from the surface. At a pressure of 300 bar, it reaches –1150 MPa in a depth of 0.1 mm. The surfaces residual stresses in longitudinal direction amount to about –400 MPa for pressures of 100 to 200 bar and change to values near –700 MPa for pressures of 250 and 300 bar. This finding suggests a change of friction conditions between ball and surface for the two named pressure regimes. With increasing rolling pressure, also the thickness of the surface layer affected by residual stresses increases. It starts from 0.1 mm at 50 bar and reaches 0.6 mm at 300 bar. Qualitatively similar observations are made for the residual stress states in circumferential direction.

The lower viewgraph allows to visualize the effect of the ball diameter at constant pressure and cross feed. Samples 8, 6, and 9 show similar surface values close to –750 MPa in longitudinal direction. With increasing ball diameter, the subsurface residual stress maximum near –1100 MPa does not change significantly but is shifted to larger depths. In a similar manner, the thickness of the surface layer affected by residual stresses increases. Evaluating the effects of different cross feeds by looking at the samples 6 and 7 or 9 and 10, respectively, it is found that the larger cross feed leads to a higher residual stress level in larger distances from the surface. The compressive residual stress maximum is not changed significantly but it is shifted towards larger distances from the surface. On the other hand, the surface residual stress values decrease with decreasing cross feed. Also in this case, the description of the findings applies in a qualitatively similar way to the depth distributions of residual stresses in circumferential direction.

Conclusions

It was found that deep rolling allows to produce smooth sample surfaces as they are desired for the interface surfaces of morse tapers for modular hip endoprostheses. The surfaces investigated were free of contamination by wear products of the rolling ball and free of contamination by particles or corrosion products.

It could be demonstrated that deep rolling allows to produce variations of depth distributions of residual stresses in a wide range by chosing the respective rolling parameters. With respect to the loading conditions described above, it appears to be favourable to create compressive residual stress states which reach to a significant depth. In this way, the superposition of residual and loading stresses can result in favourable local stress states in the area where tensile bending stresses and tensile stresses due to edge pressure of the morse taper junction occur. In this way, fatigue lifetime of the component can be increased, or the probability of fatigue crack development and propagation which might lead to an early failure is reduced.

Nevertheless, it must be kept in mind that the surface residual stress values created by the considered rolling procedures are relatively low compared to the subsurface residual stress maxima. This effect is especially pronounced for the rolling parameters which create residual stress distibutions which reach to large depths up to 0.6 mm. These low surface residual stresses will not allow to fully use the compressive subsurface residual stresses to improve local fatigue loading conditions since bending residual stress gradients are relatively small. Since fatigue cracks developing at the surface will propagate assisted by corrosive biological media, they will not reach a stable state. In view of this, the development of fatigue cracks must be completely avoided, and a surface finishing procedure subsequent to deep rolling should be identified which rises the level of the compressive surface residual stresses.

References

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