SHOT PEENING OF A TITANIUM ALLOY FOR MEDICAL IMPLANT APPLICATIONS WITH ZIRCONIA SHOT

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Abstract

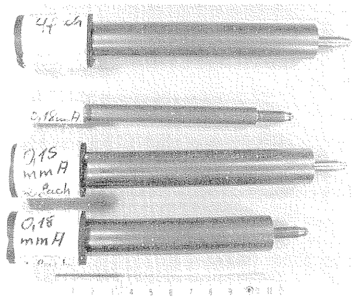
Shot peening with steel shot followed by a cleaning process with glass beads is commonly used as surface finish in the production of modular hip endoprostheses. The induced compressive residual stresses increase the resistance against fatigue and fretting fatigue. The surface roughness can be adjusted in a range that enhances the physiological acceptance / compatibility of monolithic implants. However, an increasing number of publications show that there is a significant contamination of residual glass fragments at the finished surfaces. Latest research suggested an association between glass particle contamination and increased corrosion or fretting fatigue, respectively of the morse taper junction. The particles cause damage of the natural passivation layer of the Ti-alloy since the Ti-oxides show relatively poor mechanical properties. There are also hints that particle contamination causes local osteolysis of the surrounding femur. The aim of this study was to evaluate the effects of shot peening with zirconia shot in comparison with glass and/or steel shot. Zirconia beads offer higher hardness and strength / fracture resistance than glass beads.
The surfaces of TiAl6V4 rods were shot peened with zirconia shot using different Almen intensities and coverages. A field emission scanning electron microscope was used for the detection of the residual particle contamination on the surfaces. The near-surface residual stress distributions induced by the shot peening processes were measured by X-ray diffraction. The results of the scanning electron microscopy and X-ray residual stress analyses are discussed with respect to application of the shot peening processes as finish of monolithic and modular hip endoprostheses.

Introduction

The significance of morse taper junctions of modular prostheses is discussed very controversially. There are authors who have described the negative effects of the modularity regarding the junction as well as authors who found no evidences for disadvantages. Critics argue that there are additional abrasion products due to the morse taper junction [1-14]. The contamination of the morse taper junction with body liquid can enhance corrosion in the junction gap as well as fatigue enhanced by stress corrosion cracking [11]. Shot peening with steel shot in order to induce compressive residual stresses is used to reduce the negative effects named. However, a subsequent glass bead blasting is necessary for cleaning to remove steel contamination of the surface. This combination of processes is commonly used in the manufacturing of monolithic as well as morse taper junction type modular hip endoprostheses. Publications document that residual particle contamination remains on and in the surface of the processed implants which have been implicated in early loosening of prostheses in terms of abrasive third body wear and particle-induced local osteolysis [15-19]. Moreover, the standard of Euronorm 12010 from 1998 requires prosthesis surfaces free of any residual particle contamination. The aim of this work is to present results of shot peening with zirconia shot in order to avoid remaining glass particles and to compare the results with surfaces treated by shot peening with steel shot and subsequent glass bead blastin. Finally, a method is suggested which allows to obtain surfaces free of particle contamination.

Material Investigated and Experimental Details

Rods of TiAl6V4 with diameters of 8 and 15 mm, respectively, have been shot peened with zirconia shot. The samples are shown in fig. 1. The shot used was Zirshot® Z425, Saint-Gobain ZirPro, Le Pontet, France, with a grain size of 0.425 to 0.600 mm. The outstanding properties of Zirshot are the high hardness and strength / fracture resistance. The shot peening parameters are given in tab. 1.
After the shot peening, the surfaces of the samples were investigated with a field emission scanning electron microscope (LEO 1525 Gemini) to analyze the residual particles (see [20] for principles of SEM analyses). The representative back scattering electron images were evaluated by means of EDAX with respect to the element distributions.
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 $2\theta_0=141.8°$. Lattice strains were measured at 11 positions in the angular range of $-50° \leq \psi \leq 50°$. Residual stresses were evaluated in circumferential direction of the rods according to the $\sin^2\psi$-method [21] using the X-ray values of the elastic constants $E^{\{213\}}=113$ GPa and $\nu^{\{213\}}=0.32$ (for details see [22], e.g.).



intensity [mmA]	coverage [passes at 2 x t 98%]	amount of shot [kg]	air pressure [bar]	sample diameter [mm]
0.15	2	1.4	4.5	15
0.15	4	2.8	4.5	15
0.18	2	1.4	6.0	15
0.18	4	2.8	6.0	8

Table 1: Shot peening parameters of the samples investigated.

Figure 1: TiAl6V4 rods under investigation.

Results and Discussion

The results of the residual stress analyses are given in fig. 2. Typical shot peening residual stress states are observed with subsurface maxima of compressive residual stresses in depths between 0.02 and 0.05 mm. With the Almen intensity of 0.18 mmA, the compresive residual stress maximum amounts to about -700 MPa. The effect of shot peening reaches to a depth of about 0.1 mm. According to the expectation, increasing coverage slightly lowers the surface residual stresses and shifts the residual stress maximum to larger distances from the surface. Small Almen intensities (0.15 mmA) reduce the compressive residual stress level and the affected depth. The sample with 0.15mmA and large coverage shows different characteristics.

The residual stress maximum is relatively large, and the affected depth is smaller. These differences are attributed to the smaller diameter of the sample rod (s. tab. 1). The results are compared to residual stress states created with steel shot on similar components of TiAl6Nb7 [10]. The slightly higher residual stress level is attributed to the higher strength of the material used. The subsurface residual stress maximum is not pronounced. This might partially be an effect of measuring with the hole drilling method which does not resolve the near-surface residual stress states as precise as the the X-ray method does. As expected, increasing Almen intensity increases the compressive residual stress level. Glass bead finishing seems not to have a significant effect on the residual stress state. The results suggest that shot peening with Zirshot and with steel shot allows to obtain similar residual stress states.
The findings from the SEM and EDX analyses in fig. 3 show that the surface prepared with Zirshot contains a contamination with zirconia particles.

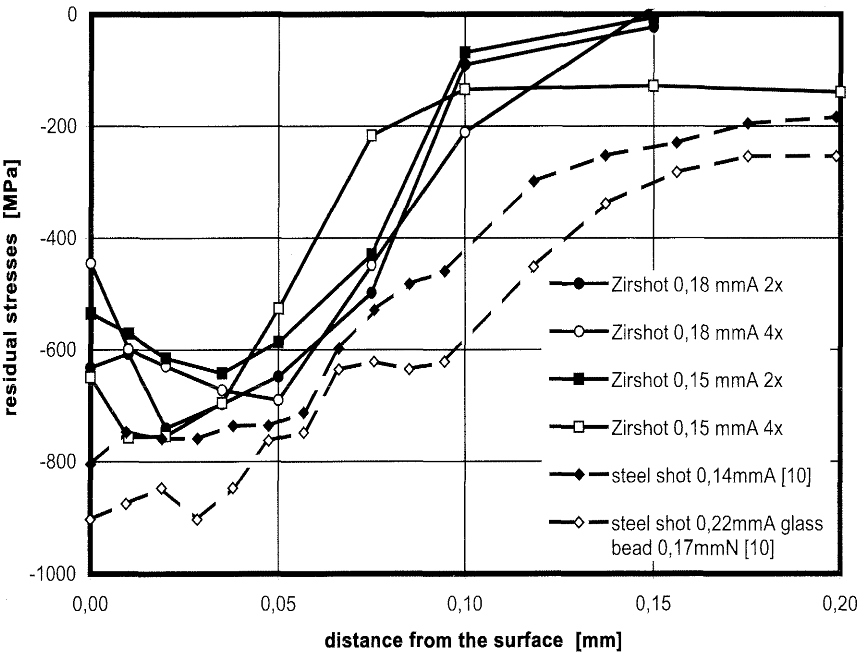


Figure 2: Residual stress states of TiAl6V4 rods after shot peening with Zirshot in comparison with TiAl6Nb7 rods after shot peening with steel shot.

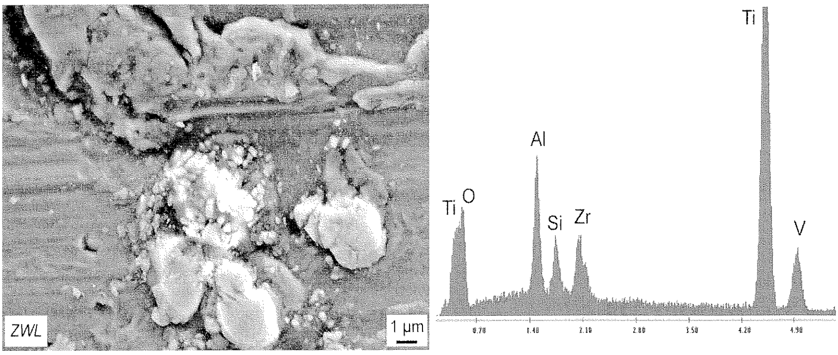


Figure 3: SEM photograph of residual particles at the shot peened surface (left) and EDX verification of zirconia contamination (right).

The fact that manufacturing processes and the material of implants play a significant role for their biocompatibility was demonstrated by [7] in his analysis about a modular femur nail. He detected osteolysis and periosteal reactions in the area of the morse taper junction on X-ray follow ups. In his work on 42 patients that were treated with a modular non-corrosive intramedular steel nail due to a fracture of the femur, 12 modular nails were removed. The morse taper junctions were examined in view of corrosion products and histopathological results. The junction showed corrosion products that adhered on the morses taper junction in an area were osteolyses were found on X-rays. It was concluded that the presence of corrosion products on morse taper junctions are the main reason for the radiological results (osteolyses, periosteal reactions and cortical thickening).

In [3], it is stated that the stress distribution within the components and the micro movements of the interface have an influence on the long-term function of modular prostheses. Bending loads can open gaps between the male and female components of the morse taper junction and allow corrosive contact with biological liquids. Tensile loading stresses can enhance corrosion and fretting fatigue. They can even lead to fatigue cracking accelerated by stress corrosion cracking. The analysis showed that bending stresses cause the largest part of local tensile loading of the morse taper junction. Cortical bridging and osseous integration in the area of the morse taper junction reduces stress peaks by 45% and reduces the separation of the morse taper junction by 55%. The author comes to the conclusion that the formation of suchlike tissues in the area of the morse taper junction can form a closed capsule which can inhibit the migration of corrosive or metallic wear products and, therefore, inhibit the biological process of bone resorption.

In his biomechanical analysis of the morse taper junction of the S-ROM prosthesis with a servohydraulic test machine and a simulation of a body weight 5 to 9 times higher at a test frequency of 60 Hz, [8] detected no mechanical failure of the 11 mm stems. There were no measurable relative movements between the male and female components of the morse taper junction when it was correctly assembled. However, the scanning electron microscopic examination of the contact zone showed surface changes as an indication for corrosion with transfer of material between the male and female components of the junction.

Several examinations could proof that in the case of blasting processes with glass beads, residual particles remain on and in the surface of the morse taper junction. They can potentially lead to increased corrosion due to abrasive third body wear [18,19]. In view of the long life cycle of morse taper junctions, such contaminations should be avoided [1, 11]. In an analysis of 4 different modular hip endoprosthesis models [11], it was shown that the contact with biological liquid of the morse taper junction can lead to "unpredictable" effects. The most likely interpretation is the presence of not thoroughly analyzed corrosion assisted wear and fatigue phenomena and physiological reactions on the products. In how far this is also related with the glass particle contamination has so far not been demonstrated conclusively [18, 19]. We therefore join [12] that morse taper junctions have to have an appropriate design in order to minimize the production of abrasive and wear particles.

Conclusions

Literature and own experimental results lead us to the conclusion that shot peening both with steel shot as well as zirconia shot allows to obtain the desired residual stress states of the implant components. However, particle contamination of the surfaces must be avoided for physiological reasons as well as for reasons of wear, fretting fatigue, and corrosion of the implant material. It is also required to fulfill the standard Euronorm 12010. The standard shot peening processes, however, lead to a contamination of the surfaces with glass or zirconia particles, respectively. Therefore, a process is suggested which was developed by some of the authors of this work [23]. It consists of shot peening with steel shot and subsequent removal of the ferrous contaminations by a pH-dependent chemical cleaning procedure. This procedure allows to avoid any ferrous or particle contamination of the implant surfaces and allows to still employ the favourable topography of shot peened surfaces with regard to the biocompatibility of the implants.

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