EXTENSION OF THE LIFE OF IMPLANTS FOR
OSTEOSYNTHESIS BY APPROPRIATE SHOT
PEENING OF THE SURFACE

W. Winkler-Gniewek and M. Ungethum

Department of Research and Development, Aesculap-Werke AG,
D-7200 Tuttingen

ABSTRACT

Shot peening, a procedure more and more applied in technology for surface treatment of dynamically stressed components, has been critically examined with regard to its suitability for implants for osteosynthesis. The approximately 50% increase of the bending fatigue strength in laboratory air is independent of the shot type, especially in the case of stainless steel or ceramic shot. Ceramic shot is, however, the only medium which leaves the required level of corrosion resistance unaffected in a simulated physiological solution. Provided therefore the process is restricted to non-metallic shot, this treatment is a suitable means of reducing damage due to fatigue fractures and increasing the safety of implants and prostheses.

KEYWORDS

Shot peening, fatigue, corrosion, implants for osteosynthesis.

1. Introduction

The long years of clinical experience with implants for osteosynthesis have included the failure of such implants due to premature fractures. There are many reports of this in the literature (2,4,5,9,10,12,13,14,15,16,18,23,24,26,27,30,35,36). It is now generally accepted that the reason is to be found in the majority of cases in a material fatigue resulting from an excessive alternating stress, although the participation of local corrosion processes is also possible. These fractures occur after varying intervals of time and are mainly observed in the area of drill holes originating from the smallest cross-section (Fig. 1).

The degree of stress is primarily determined by the choice of implant (size and shape). On the other hand it is influenced by the design (cross-section and drill holes), but an incorrect introduction of a plate (by means of a free drill hole in the vicinity of the fracture) and an inadequate stabilization by screwing (in the case of a complex multiple fracture) can also lead to increased stresses. The absence of the bone support after the opera-
tion will also expose the implant to bending stresses, if the body load is applied prematurely. The full weight body will be transmitted to the implant over a long period in the event of incomplete healing.

The fatigue strength constitute only a fraction of the tensile strength provided by a metallic material, especially where critical stress states such as bending and torsion are present, and it is determined to a large extent by the type of material and its state. Type CrNiMo 1812 corrosion-resistant stainless steels as specified in Standard ISO 5832/1, are used for implants for osteosynthesis. Preference is given to the cold-worked state where stringent strength requirements have to be met. The fatigue resistance is also influenced to a large extent by the design. Notches or abrupt cross-sectional transitions have an unfavourable effect on stress states, reducing the fatigue strength. Surface processing also has a substantial contribution to fatigue behaviour. It is well known, for example, that grooves or scratches can initiate a fatigue crack (Fig. 2a).

There are limits to the freedom of choice of materials. The only materials that can be considered are those which are inert and compatible in the body. The design of implants is also restricted by their function and by anatomical conditions. The surface is in general polished, so that inhomogeneities are evened out. In the technical field an increasingly wide range of methods of surface treatment have been developed recently, since it is in fact in the region of drill holes and changes in the cross-section that the life of components and their fatigue strength under dynamic stress can be improved. One of the most important and simplest methods is shot peening of the surface, i.e. the projection against it of steel or glass shot. It has been found that the life can be extended several fold and the fatigue strength significantly increased both by surface hardening and also in particular by the introduction of residual compression stresses in the surface (21).

One disadvantage of this method, if steel shot is used, is the possible contamination of the surface by foreign materials, causing a loss of corrosion resistance in passive materials. Glass balls exhibit a neutral behaviour in this connection, but they are liable to break, giving rise to splinter formation after a short period of treatment and necessitating frequent control
checks and removal of shot. This can be seen as an obstacle to the development of shot peening in particular fields of technology. Shot of stainless steel quality is seldom obtainable on the market and resistant ceramic materials have only recently become available for this purpose. The present paper examines the effects on the fatigue strength and corrosion resistance of implants for osteosynthesis of shot peening with stainless steel and ceramic shot. The life and fatigue strength are determined on samples by means of the cyclic bending test in accordance with DIN 50113, the Wöhler curve for the samples in the polished state being compared with that of samples after shot peening. The effect on the corrosion resistance of both variants is also compared with that of the normal state.

2. Service Life and Fatigue Strength Studies

The samples were taken from circular material with the following chemical composition in accordance with Standard ISO 5832/1:

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.014</td>
<td>0.34</td>
<td>1.87</td>
<td>0.017</td>
<td>0.007</td>
<td>17.66</td>
<td>2.74</td>
<td>14.18</td>
</tr>
</tbody>
</table>

wt.%

The static mechanical characteristics, determined by the tensile test in accordance with DIN 50145, were found to be:

\[ R_m = 930 \text{ N/mm}^2; R_{p0.2} = 740 \text{ N/mm}^2; A_5 = 23\% \]

A circular sample 5 mm in diameter was selected as the sample shape for the cyclic bending test. After polishing, some of the samples underwent shot peening with stainless steel shot having a strength of 2300 N/mm\(^2\) and a diameter of 0.4 mm in a compressed air unit until complete coverage was obtained, followed by cleaning and smoothing with smaller shot 30-50 \(\mu\text{m}\) in diameter. The remainder of the samples were treated with ceramic shot having a diameter of 0.25-0.425 mm and a hardness of 65 HRC and subsequently with smaller ceramic shot having a diameter between 63 and 180 \(\mu\text{m}\) (Fig. 2b).
The vickers surface hardness increased from 328 HV5 in the polished samples to 391 or 381 HV5 in the samples which had undergone shot peening with steel or ceramic shot. This surface hardening extended from the surface layer between 0.05 and 0.1 mm into the depth of the material, as was evident from microhardness measurements on a metallographic polished section. The roughness was determined from a roughness profile (Fig. 3), being maximal in the case of samples peened with steel shot, which had an arithmetic mean value $R_a = 2.6 \mu m$. Values of $R_a = 1.3 \mu m$ were found after peening with ceramic shot, compared to $R_a = 0.10 \mu m$ in the polished state.

The fatigue tests were carried out on a PUNZ cyclic bending test machine manufactured by Schenck, operating at a frequency of 100 Hz in laboratory air. Since we were concerned both with the life strength, in which the samples have a finite life at a particular stress, and also with the fatigue strength range, in which the life is almost infinitely great, no strict calculation of the statistical significance of the characteristics was carried out. The methods which have been widely discussed in the literature (6,7,8,22,25,32,34) require for each state, for the determination of the fatigue strength alone, a minimum number of samples between 20 and 30 in the transitional range and at least as many samples for the life strength determination. Since it had been shown by preliminary service life experiments that large differences were to be expected between the untreated state and the state after shot peening, an estimate of the increase in service life and fatigue strength was sufficient by the planning and evaluation of the experiments in accordance with DIN 50 113.

![Fig. 3 Roughness profile after shot peening a) with steel shot, b) with ceramic shot, c) in the grounded and electropolished state](image)

To determine the Wöhler curve several samples were tested at a particular stress level, a closer comparison being made of the life strength region for untreated samples with that for samples which had undergone shot peening with stainless steel shot. The fatigue strength region was then examined in greater detail for samples which had undergone peening with ceramic shot. This made it possible at least to estimate the dispersion in the characteristic values and to make a more reliable statement on a statistical basis.
It was immediately clear from a comparison of the Wöhler curve for the polished and shot peened state (Fig. 4) that the service life of an implant can be enormously increased by shot peening, depending on the load conditions. Assuming that an implant is exposed to about $10^6$ changes of load in a year, the stress may not for example exceed 350 N/mm$^2$ for the untreated polished state if the implant is to remain intact after this period. Whereas with a stress level of 475 N/mm$^2$ only 2 months would pass before fracture, the corresponding figure in the shot peened state would be 200 months, i.e. more than 16 years, before the implant fractured. The service life at this stress level has therefore been increased by a factor of 100 as a result of shot peening, while at a lower stress level it becomes almost infinitely great. For a given service life of $10^6$ load changes, the stress can be increased to 525 N/mm$^2$ in this state, i.e. 50% more than if the implant had not undergone shot peening. According to Wöhler, the high cycle bending strength for the untreated state is 325 N/mm$^2$ for $10^7$ load cycles, and for the state after shot peening with stainless steel shot 500 N/mm$^2$.

![Wöhler curve for the state after shot peening](image)

This also corresponds to an increase of about 50% in the fatigue strength. Although the experiments were continued in some bases beyond $10^7$ load cycles and fractures still occurred in this case, the samples were formally assessed as fatigue-tested without fracture.

The fatigue strength is increased by approximately the same extent by treatment with ceramic shot as by treatment with steel shot. Although the anticipated service life values in the transitional range of the fatigue strength exhibit dispersion by a factor of 3 to 5, the fatigue strength in the cyclic bending test may be given by 490 N/mm$^2$. It is clear here again that fractures may still occur below this level, if the experiments are continued beyond $10^7$ load cycles. With a stress of 450 N/mm$^2$, however, no fracture was obtained even after $7.8 \times 10^7$ load cycles, and the experiments was interrupted. This load cycle number corresponds on the above assumptions to a complete human life. The results have been summarized in Table I.
Table 1. Summary of the results of fatigue strength studies

<table>
<thead>
<tr>
<th>Surface state</th>
<th>Surface hardness HV 5</th>
<th>Roughness $R_a$ (µm)</th>
<th>Depth of roughness $R_t$ (µm)</th>
<th>Fatigue strength $\sigma_e$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grounded + electropolished</td>
<td>328</td>
<td>0.10</td>
<td>0.48</td>
<td>325</td>
</tr>
<tr>
<td>Shot peening with ceramic shot</td>
<td>381</td>
<td>1.3</td>
<td>8.6</td>
<td>490</td>
</tr>
<tr>
<td>Shot peening with stainless steel shot</td>
<td>391</td>
<td>2.6</td>
<td>17.4</td>
<td>500</td>
</tr>
</tbody>
</table>

3. Corrosion Studies

Determination of the corrosion behaviour was carried out by means of electrochemical investigations with a corrosion measurement cell. The measurement layout was designed in accordance with the corrosion test standard ASTM G5. Both current density/potential and also current density/time curves were recorded, as proposed in the corrosion test standard for surgical metallic implant materials ASTM F4 for the determination of the pitting and crevice corrosion potential.

Cylindrical samples 60 mm in length and 6.35 mm in diameter were used as test elements, immersed in the test solution over a length of about 20 mm. For determination of the crevice corrosion potential, a teflon ring 3.18 mm in thickness with a conical bore hole corresponding to a defective fit of ± 0.38 mm was placed over the sample in accordance with the recommendations in ASTM F4. After polishing, some of the samples underwent shot peening with stainless steel shot and subsequent treatment as indicated above, while the remainder were shot peened with ceramic shot. The test solution was a 0.9% NaCl solution at 37°C corresponding to physiological conditions, which had undergone purge with nitrogen.

After adjustment of the rest potential, which was monitored as a function of time, the potentiokinetic current density/potential curves were recorded by anodic polarization with 1 mV/s (Fig. 5). On reaching the breakdown potential, defined as the point at which the current density exceeded 500 µA/cm², back-polarization was carried out until the hysteresis loop was closed. The pitting potential was determined on passing below a current density of 500 µA/cm². The results were evaluated in tabular form (Table 2).

The rest or corrosion potential after a few days for the polished samples was +190 mV against a calomel electrode in the passive range; this value was very different from the pitting potential with a value of +245 mV, which was again only half the breakdown potential of +500 mV. The corrosion potential for samples after shot peening with stainless steel shot was -100 mV in the active corrosion range. Values extending down to -600 mV were recorded immediately after immersion, thus indicating that the corrosion resistance had been greatly reduced, probably by metal transfer. The corresponding reduction in the breakdown potential to +180 mV and the pitting potential to +120 mV also indicates a reduction in the corrosion resistance as a result of shot peening with stainless steel shot. A visible rust coating could also be observed after the test. The state after shot peening
Fig. 5 Current density/potential curves for the state after shot peening with a) stainless steel shot, and b) ceramic shot, in comparison with c) the grounded and polished state.

Table 2. Summary results of the corrosion investigations

<table>
<thead>
<tr>
<th>Surface state</th>
<th>Rest potential ( \text{mV}_{\text{SCE}} )</th>
<th>Breakdown potential ( \text{mV}_{\text{SCE}} )</th>
<th>Pitting corrosion potential ( \text{mV}_{\text{SCE}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grounded + polished</td>
<td>+ 190</td>
<td>+ 500</td>
<td>+ 245</td>
</tr>
<tr>
<td>Shot peening with ceramic shot</td>
<td>+ 170</td>
<td>+ 465</td>
<td>+ 270</td>
</tr>
<tr>
<td>Shot peening with stainless steel shot</td>
<td>- 100</td>
<td>+ 180</td>
<td>+ 120</td>
</tr>
</tbody>
</table>

with ceramic shot was also compared with the polished state. The rest potential was in this case + 170 mV, the pitting potential + 270 mV, and the breakdown potential + 465 mV, in both cases taking into account a dispersion of the same order of magnitude as in the normal state. This indicates clearly the advantage of shot peening with ceramic shot.
In order to check whether the behaviour of the implant material was negatively influenced by this form of treatment also under unfavourable conditions, for example in the area of a crevice, the crevice corrosion potential was determined in accordance with ASTM F4 for the two states concerned (unpeened and ceramic shot peened). A crevice corrosion potential of +250 mV was recorded in both cases (Fig. 6), and has virtually the same value as for the pitting potential. Since the rest potential is below this value, the material appears in both cases to be adequately resistant to pitting and crevice corrosion under simulated physiological conditions. This agrees also with the requirement of various authors (20, 33, 36) for an effective sum of elements of 26 as given by Lorenz and Medawar (19). In the present case the effective sum was 26.70. The two states can therefore be regarded as equivalent as regards their static corrosion behaviour.

4. Summary and Discussion

The results quoted above show that a substantial improvement in the fatigue properties can be obtained by a surface treatment in the form of shot peening. No undesirable effects on the corrosion resistance are liable to occur if a suitable type of shot is selected. The use of ceramic shot, for example, led to a 50% increase in the cyclic-stress bending strength by comparison with the polished state, from 325 N/mm² to 490 N/mm² in the case of a tensile strength of 930 N/mm². The otherwise restricted service life in this load cycle (e.g. 450 N/mm²) is almost infinitely great with a comparable corrosion resistance.
The Life of Implants for Osteosynthesis

Treatment with steel shot is not recommended both because surface contamination is liable to occur even in the case of a similar composition and because it would be difficult to impart the necessary strength for shot peening to a stainless steel of the same composition as the implant material without including additives such as carbon.

Other forms of corrosion such as stress corrosion cracking or fatigue corrosion which may occur in implant steels, have not been examined here. These steels are in fact already known to be resistant to stress corrosion cracking (23,35,36). Fatigue corrosion on the other hand, does occur to a certain extent as with any other material, producing a reduction in the service life or indeed a general reduction in the fatigue strength, depending on the load frequency, the type of loading and also the passivation and pitting or crevice corrosion behaviour. Geometrical factors resulting from the design, processing, etc., play an important part here, so that exact data are only feasible in the case of a component test.

Since the corrosion behaviour is not substantially altered by shot peening treatment, it may be assumed that the improvement in the fatigue properties will also be retained under fatigue corrosion conditions. It is known, for example, that the stress corrosion cracking and fatigue corrosion behaviour may even be improved by shot peening (31), so that a better ratio of the fatigue behaviour in physiological solution to the fatigue behaviour in air might on occasion be obtained for the shot peened state in comparison with the untreated state.

It has been assumed by various authors that the occurrence of fatigue corrosion is linked with a sensitivity to crevice corrosion (1,17), and stainless steel is regarded as more sensitive to this form of corrosion than other implant alloys based on cobalt or titanium (29). Processes are known, however, involving the remelting or adjustment of determined concentrations of alloy elements, whereby this type of corrosion can be substantially reduced in the case of steel. Some authors have in fact found that in typical implant steels the fatigue properties are only very slightly influenced by fatigue corrosion (3). Shot peening with ceramic shot can therefore be recommended both for implants for osteosynthesis and also for other implants. A similar form of processing is already being used for prostheses, apart from the sliding surfaces. Although few systematic studies have been carried out on this behaviour, some authors have been able to show that a definite improvement can be obtained in the fatigue strength of the usual prosthesis materials (11,28), even under physiological conditions.

REFERENCES

(8) Deubelbeiss, E. Materialprüf. 16 (1974), Nr. 8.
(22) Maenning, W.W. Materialprüfung 13 (1971), Nr. 1.