CIRP Annals - Manufacturing Technology

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--Manuscript Draft--

Manuscript Number:	CIRP-2023-S-09R1
Article Type:	STC S
Keywords:	Surface modification, Biomedical, Burnishing
Corresponding Author:	Domenico Umbrello, PhD Rende, ITALY
First Author:	Giovanna Rotella, PhD
Order of Authors:	Giovanna Rotella, PhD
	Francesco Cosco, PhD
	Maria Rosaria Saffioti
	Domenico Umbrello, PhD
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Evaluation of fretting corrosion fatigue in burnishing of *Ti6Al4V* component for artificial hip joint

Giovanna Rotella[a], Francesco Cosco[b,c], Maria Rosaria Saffioti[b], Domenico Umbrello[b]* (2)

[a]*Department of Management, Finance and Technology, University LUM Giuseppe Degennaro, Casamassima, BA 70010, Italy*
[b]*Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende, CS 87036, Italy*
[c] *Siemens Digital Industries Software, Leuven, 3001, Belgium*

Modular hip replacements provide a flexible way to reconstruct the joint with optimized biomechanics, but one of the most common causes of modular hip prostheses failure is the fretting corrosion at the neck-head interface combined with their related micro-motion. In this context, the present study aims to improve the neck surface strength by means of burnishing process. An experimental campaign on *Ti6Al4V* hip joint neck was carried out at varying burnishing parameters, namely force and speed. The main surface integrity parameters affecting the neck performance have been evaluated, namely mean surface roughness, micro hardness, affected layer and microstructure. Afterwards, fretting corrosion fatigue tests on necks and alumina ceramic heads were performed under standard conditions simulating human walking. The relative motions at the neck-head interface were analyzed by an innovative technique able to detect changes during the test with high accuracy.

Surface modification, Biomedical, Burnishing

1. Introduction

Hip replacement surgery is very often used to relieve pain and restore function in unhealthy hip joints. Usually, modular hip joints are employed and a combination of different materials for the neck and the head are used to produce high quality implants, which lead to a variety of advantageous combinations, such as cobalt chrome or ceramic heads on titanium necks [1, 2]. In particular, *Ti6Al4V* titanium alloy is often chosen for the neck part due to its high strength, low Young's modulus comparable to the one of the bones, and for its high biocompatibility within metallic biomaterials. Concerning the head, alumina ceramic is often used for young patients compared to the cobalt chrome one which generally applies to elders [3, 4]. Thus, even though modular hip replacement provides high flexibility to reconstruct the joint with optimized biomechanics, they are susceptible to fretting fatigue and corrosion at the neck-head interface which can lead to adverse tissue reactions and implant failure. The above components are connected by the neck conical part and, during simple daily activities, are in relative motion to each other, causing fretting and abrasion at the conical head-neck connection. Also, material degradation occurs due to the effects of the surrounding body fluids [5]. Afterwards, the corrosion releases toxic metal debris causing local tissue damage and painful inflammation with long-term systemic effects as the toxic debris spreads throughout the body, eventually leading to revision surgery [6]. For this reason, it is necessary to deeper study fretting corrosion phenomena on biomedical implants for hip replacement to improve their reliability allowing to fabricate new generation ones suitable for young and sports people. In fact, one of the related issues with actual fabrication systems is the difficulty to considerably improve artificial hip components in order to make them significantly superior in terms of performance, reliability and durability [7]. Thus, in order to obtain high quality artificial hip joints, innovative post processes, such as burnishing, texturing, laser peening, etc., can be used to reduce friction and wear of artificial implants [8] modifying the metal component surface prone to deteriorate under fretting corrosion and, consequently, improving the overall implant reliability and service life [8-10]. However, executing fretting corrosion tests to verify the performance of a modified prosthesis element can be time consuming and difficult to carry out since it needs to follow strict technical standards [11, 12]. Due to the physiology differences of the human body between individuals, it is challenging to simulate all real-life effects on implants in the laboratory. As a result, test protocols have been developed, specifying load level, test duration and appropriate liquid solution, to better suit the intended purpose on implant investigations [11, 12]. Also, comparison between different surface states are critical issues to assess since tests involve, most of the time, the need to fail the component which cannot be accelerated when the tests are performed under usual clinical conditions. Among all emerging sensing technologies in the field of non-destructing optical testing, phase-based motion estimation (PBME) can result as a valid tool for assessing the surface gradual degradation before failure, due its higher sigma-to noise ratio (SNR) compared to similar technologies, and also because it does not require any complex modification of the observed specimen, apart from the addition of manually shaped dot markers [13]. The mathematical properties of the transform allow PBME having unprecedent accuracy and robustness to noise technologies, working far beyond the 0.01-pixel resolution limit, thus outperforming other more affirmed technologies, such as DIC (Digital Image Correlation). The comparative nature of PBME, based on extracting relative displacement with respect to a given reference, offers a robust solution, which can intrinsically cope with the optical aberration due to the air-liquid refraction. Therefore, the focus of this study is to fabricate higher quality neck component by means of burnishing. Also, it aims to validate a new methodology for comparative estimation of fretting corrosion fatigue on necks of modular hip prostheses, in an environment similar to the human body and according to actual regulations.

2. Materials and Methods

The workpieces used for the experimental tests were *Ti6Al4V* conical hip joint necks with a diameter from 12 to 14 mm and 12 mm conical length. The initial hardness was measured to be 387 $HV_{0.1}$. The samples typical α equiaxed grains with intergranular β microstructure was also verified. *TiAlN+Al_2O_3+TiAlN* coated inserts have been employed for machining (*CNMG 12 04 08-MF 1115*) with standard semi-finishing turning parameters while a similar coating was used for subsequent roller burnishing (*SRD52-2.5R-0–85-CRB*). Turning tests were conducted on a CNC high-speed turning center (cutting speed 70 m/min, fixed feed rate 0.1 mm/rev, depth of cut 0.05 mm). Afterwards, the burnishing process was executed at four different levels of burnishing force (1000, 1500, 2000, 2500 N), three different level of speed (50, 100, 150 mm/min), a tool radius of 2.5 mm and burnishing feed of 0.05 mm/rev. The above parameters were chosen based on results of a previous study [14]. Cutting and burnishing tests have been performed under minimum quantity of lubrication (MQL) conditions consisting into applying vegetable oil through an external nozzle to the tool-workpiece interface with a flow rate of 60 ml/h. Two different batches of samples were burnished (three replications for each condition in each batch) in order to carry out surface roughness and microhardness prior fatigue. Furthermore, the as turned sample was also included in the analysis as a typical manufacturing reference. In detail, the arithmetical mean height (*Sa*) and the maximum height (*Sz*) on the surface were measured using a non-contact white light interferometry based profilometer with a vertical resolution of 0.01 nm and a vertical measurement range up to 10 mm. Ten measurements for each sample were acquired along the surface in order to have statistically accurate dataset. Each sample was subsequently sectioned, embedded into a mounting resin and polished for optical microscope analysis and microhardness measurements. The grain size was evaluated using the intercept length method according to ASTM E112-13 [15]. The microhardness ($HV_{0.1}$) of samples surface and subsurface was also measured using an instrumented micro indenter with a dwell time of 10 s. The second batch was instead used for fretting corrosion tests. The equipment was designed to induce fatigue, wear, and corrosion damage at the modular neck-head interface according with the ISO7206 [12]. In detail, the equipment was developed considering the sample position according to the offset angles α (10°±1°) and β (9°±1°) as well as the femoral neck shaft angle formed by the prosthesis and the vertical direction of load application chosen equal to 130° for normal proximal femoral anatomy [5]. Angles have been selected considering the distance from the centre of the femoral head to the distal point of the stem (Figure 1). Thus, the designed set-up allows to properly orient the neck obtaining a combined axial and torsional load. The set up was mounted on a servo-hydraulic testing machine according to ASTM F1875-98 [11]. In order to simulate the connection applied during surgery (usually carried out with a medical hammer) an equivalent compression pre-load of 1800 N was applied before running each test. During the fretting corrosion test, a walking movement was simulated, for a long period of time (counted in terms of number of cycles), in order to test the prosthesis useful life, according with the following procedure: i) a compression-compression fatigue test was performed with a stress ratio, *R*, of 10; ii) the test was carried out at a frequency of *5 Hz* for a period of 10^6 cycles; iii) the head-neck interface was submersed in a phosphate buffered saline (PBS) solution, which was maintained at a temperature of 35 ºC to accelerate the corrosion reaction. The PBS solution with a pH of 7.4 ± 0.1 was selected to mimic the human body fluids. The advantage of using a buffered solution was to maintain a constant pH of the solution preventing it from becoming acidic or alkaline, thereby affecting the corrosion rate of the tests. Figure 1 reports the test setup for both burnishing and fretting corrosion fatigue tests. Afterward, the neck weight loss (using a laboratory precision balance with a resolution of 0.01 mg) and the assessment of the modular interface damage caused by fretting wear and corrosion were evaluated by means of PBME [13]. The overall method relies on computing the complex Steerable Pyramid of each frame of a video sequence, and then to extract the motion field of the observed object by looking at the local shifts of the phase of the complex value coefficients. In particular, time series of the head-to-neck relative motion has been extracted for each test combination by averaging the region of interest defined by the dot markers placed on both head and neck. Two seconds time series, sampled at 1 *kHz*, were acquired at fixed number of cycles namely test start (N=0), $2.5x10^5$, $5x10^5$ and 10^6 cycles. Each time series was then computed to extract the average amplitude and direction of relative vibration pattern which, in turn, describes the wear of the neck during the test.

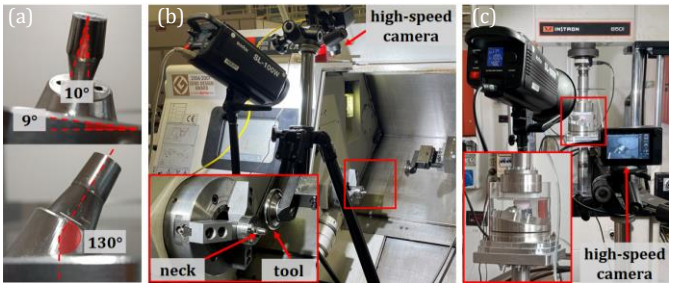


Figure 1. Offset angles and the femoral neck shaft angle (a), overall setup for both burnishing (b) and fretting corrosion fatigue tests (c).

3. Results and discussion

3.1. Surface roughness

The measured surface roughness of the as turned neck bars was of about 0.84±0.1 µm for arithmetical mean height (*Sa*) and 7.66±0.63 µm for the maximum height (*Sz*). Burnishing process significantly improved the surface quality as roughness considerably decreased especially, as shown in Figure 2, increasing the burnishing force. Also, rising burnishing speed translates into a reduced surface roughness even though the influence of such process parameter is less pronounced than burnishing force. This is due to the effectiveness of the ploughing effect to significantly smooth the surface. Moreover, no flaking phenomenon was encountered for all the investigated forces implying they were not reaching a critical value where the shear failure in the substrate layer is responsible of a reduced surface quality.

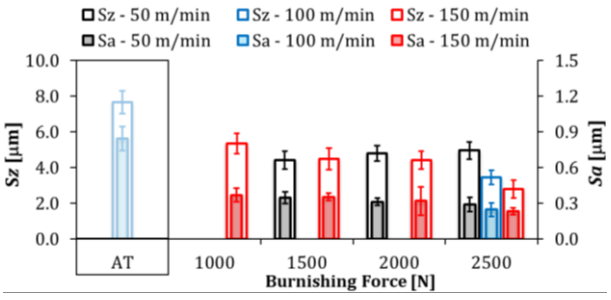


Figure 2. Height (*Sa*, *Sz*) roughness parameters on turned (AT) and burnished samples at varying process conditions (the error bars indicate standard deviation).

3.2. Microhardness and microstructure

As shown in Figure 3, a greater increase of surface and subsurface hardness is observed after burnishing process than turning. A deeper deformed layer and larger localized cold-worked zones are revealed when increasing the burnishing forces resulting into a significant rise of surface and subsurface hardness. As found for surface roughness, burnishing speed affects the overall surface hardness at a lower extent than forces as also expected from some literature findings [8]. The influence on surface changes when samples are turned or burnished is shown in Figure 4. In particular, the micrographs highlight the effects of the severe cold work with grain distortion and the formation of the affected layer. The latter gradually approaches the values of the bulk one in terms of both plastic deformation, grain size changes and hardness variation according to the used parameters. Furthermore, in the severe plastic deformation (SPD) layer, the grain size ranges within 7 μm (as turned), 6 μm (lower burnishing force) and 5 μm (higher burnishing force) while the average grain size of as received sample was of about 18 μm.

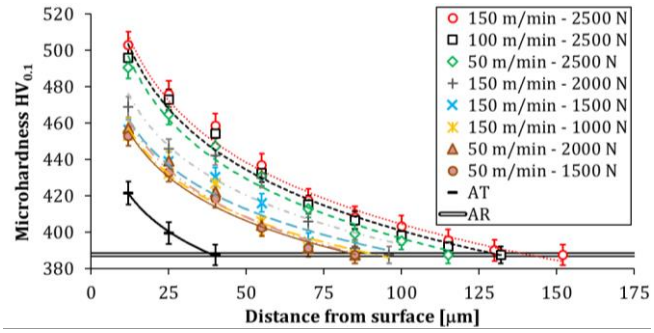


Figure 3. Surface and subsurface microhardness on as received (AR), as turned (AT) and burnished samples at varying process conditions (the error bars indicate standard deviation).

3.3. Fretting corrosion fatigue

Figure 5 summarizes the postprocessing pipeline adopted for capturing the aging effects of the fatigue testing, on each of the considered samples. By means of PBME, the time-series of the head-to-neck relative motion (taking place at the plane parallel to the camera sensor) were extracted.

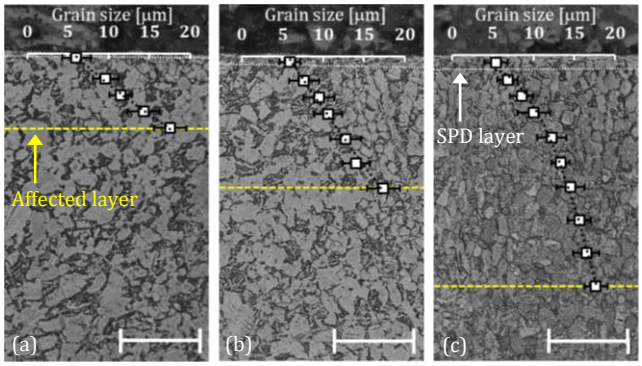


Figure 4. Grain size, SPD and affected layers for as turned sample (a) and samples burnished at 150 m/min as speed using a burnishing force of 1000 N (b) and 2500 N (c), respectively (scale bar = 50 μm).

Due to the cyclicity of the excitation, it is reasonable to expect some kind of aberrations of the initial vibration patterns, in relation of damages initiating and eventually accumulating at the head-to-neck interface. The top and bottom image sequences represent the minimum and maximum condition of the imposed loading cycles, at different stages of the fretting corrosion fatigue evolution. At the start, the vibration pattern (the white arrow) is centered at the origin of the reference and aligned with the symmetry axis of the neck. From $2.5x10^5$ cycles, vibration pattern is obtained by subtracting the average position (reported as a white and black circle in Figure 5), from the peak min-max values (green, cyan, red arrows) extracted from the timeseries. This allowed to separate the instantaneous nature of the vibration from the fretting corrosion fatigue effects accumulated on the average position. In fact, a dislocation of the vibration average position can be appreciated from $2.5x10^5$ cycles, indicating that the head is progressively moving towards the neck, whereas direction and amplitude of the vibration patterns remains unchanged. This general trend is confirmed by looking at both $5x10^5$ and 10^6 cycles where, in addition to an increase of the average dislocation, it can be also noted subtle variations of both amplitude and direction of the relative vibration vectors. By means of PBME it is possible to draw the overall behavior of all the other tested samples in terms of the magnitude and phase of the average relative displacement between head and neck. In particular, as reported in Figure 6 the better surface conditions and harder surface layer play a positive key role on reducing the head-to-neck relative motion.

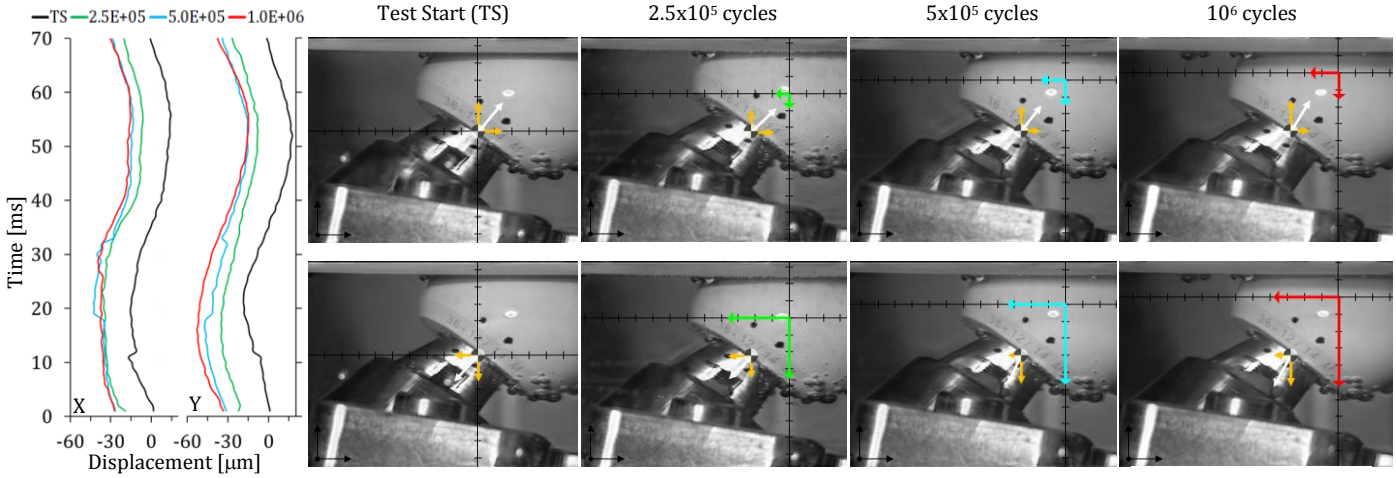


Figure 5. Left: relative head-to-neck displacement timeseries resulting from PBME. Right: maximum and minimum images of the specimen at different aging conditions, illustrating the evolution of the vibration pattern (scale unit = 10 μm).

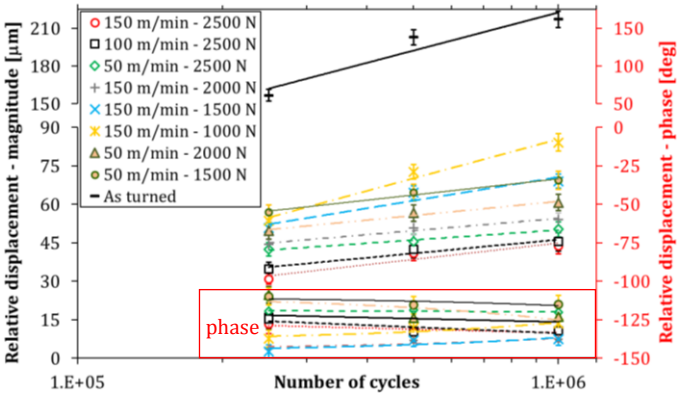


Figure 6. Magnitude (black scale) and phase (red scale) of the relative displacement obtained by PBME for all the investigated cases (the error bars indicate standard deviation).

Therefore, burnished samples are superior in terms of performance, reliability and durability compared to those turned especially when higher burnishing forces are used. It is also important to highlight that the magnitude of the relative displacement rises faster with increasing the number of cycles for the cases with the same speed but lower burnishing force. This trend is generally confirmed, although is less pronounced, by selecting lower burnishing speed for a fixed burnishing force. Finally, there is some change even in the phase of the relative displacement at varying the number of cycles and process conditions although the overall trend is that the head is moving along the symmetry axis of the neck. Figure 7 reports the measurements of the neck weight loss after fretting corrosion fatigue tests, underlying the positive effect of harder and smoother surface. In fact, the superior surface quality obtained by higher burnishing forces is confirmed by the reduced chipping of the neck during the tests. Furthermore, the combination of higher burnishing force and speed gives the smaller material loss leading to a superior performance of the whole prosthesis.

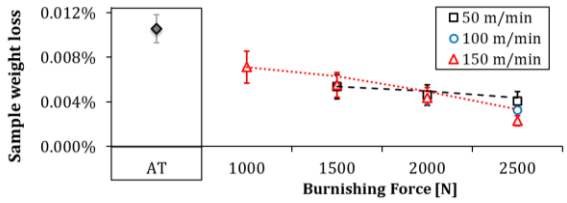


Figure 7. Percentage of weight loss on turned (AT) and burnished necks at varying process conditions (the error bars indicate standard deviation).

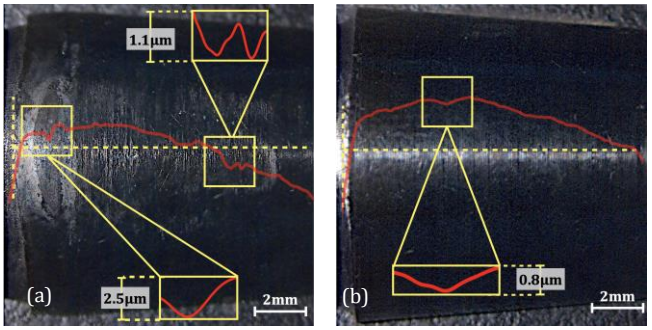


Figure 8. Wear tracks of samples burnished at 150 m/min as speed using a burnishing force of 1000 N (a) and 2500 N (b).

These findings are also in accordance with those revealed by the wear track reported in Figure 8 where the deeper wear trace is found at smaller burnishing force while smaller pitting is visible when higher burnishing forces are used to produce the neck. It is worth noting that minor pitting leads to smaller debris produced during the prosthesis service life, which translates into a safer condition for the patient.

4. Conclusions

The paper presents an experimental campaign on modular hip joint with the aim to obtain superior performance of the neck part. Thus, since the surface state dictates the component behaviour under real life conditions, particular attention has been paid in improving the surface integrity by burnishing. In particular, the performed experiments highlight the potential of the above process to fabricate a smooth and hard surface able to age slower than those available with standard manufacturing technologies. The efficient cold work ploughing achieved at higher burnishing forces, allows the neck to significantly reduce the amount and size of debris generated during the wearing process limiting the risk of local tissue damage, painful inflammation, long-term systemic effects, and, eventually revision surgery. Such effects consequently lead to a safer condition for the patient and lower chance of implant failure. Finally, the presented work demonstrates a viable way to test the overall component life under service conditions, in a laboratory environment, by developing an alternative methodology to complain with actual testing standard. Therefore, PBME has been successfully used to estimate the fretting corrosion fatigue of the implant modules, drastically reducing the time needed to obtain reliable results.

Acknowledgements

This research was supported by Ministry University Research (MUR) within the PRIN 2017 project BIONIC (201742RB8R).

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