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Forming of the titanium implants and medical tools by metal working

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ABSTRACT

Purpose: of this paper is to present some technological problems with forming of the titanium implants and medical tools by the plastic working methods.

Design/methodology/approach: Application of the new biomaterials such as titanium alloys needs to carry on tests on optimisation of the methods and parameters of the plastic working, therefore some experiments in order to determine the friction coefficient or analyse the influence of the cutting methods on the cut-surface appearance were done.

Findings: As far as stamping is concerned, it was found that the proper lubrication not only decreases frictional resistance but also limits or even completely eliminates creation of the titanium “build-ups” on the tools. As far as cutting methods are concerned, the cut-surface significantly depends on the applied cutting method. Guillotining, laser and abrasive waterjet cutting were taken into consideration. Guillotining and laser cutting influence the titanium microstructure mostly. Abrasive waterjet cutting does not cause any changes in microstructure.

Research limitations/implications: An application for the implants almost unworkable biomaterials, such as titanium alloys, needs overcoming many technological barriers such as proper selection of the lubricant, deformation temperature, strain velocity etc. Moreover, titanium belongs to the very expensive materials, so material costs are the main research limitation.

Practical implications: The investigations of the friction coefficient or the influence of the cutting method on the cut-surface quality are important for producing both implants and surgical tools by such methods as: cutting, blanking, bending, stamping, etc.

Originality/value: There are only a very few works on the sheet-metal forming processes of the titanium alloys, so each new information on the titanium deformation is valuable.

Keywords: Plastic forming; Implants; Biomaterials; Titanium alloys

MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

In the last decade there was an increase in demand for different implants applied to orthopaedics, cardiosurgery, oral and maxillofacial surgery etc. A common application of the different implants in medicine became possible thanks to:

- biomaterial development,
- introduction of the new surfacing methods,
- elaboration of more and more excellent construction both implants and instrumentarium used for their fixation,
- intense tests of the biomaterial tribological properties and processes occurring in the “implant-bone tissue” system.

A further development of Biomedical Engineering, especially production of the new, more excellent implants, strongly depends on the technology progress. An application for the implants almost unworkable biomaterials, which have high mechanical properties, needs overcoming many technological barriers. Ti6Al4V titanium alloy and Ti-Al-Nb or Ti-Nb-Zr - alloys of new generation are such materials [1, 2, 3, 4, 5]. Therefore, the work discusses some problems with plastic working of titanium alloys.

2. Some examples of the titanium alloy implants applied to biomedical engineering

High and specific requirements such as:

- high mechanical properties, especially fatigue strength,
- good corrosion resistance,
- biocompability, biotolerance,
- lack of tendency to thrombus creation in the blood contact,
- favourable tribological properties,

which biomaterials should have, limit the amount of materials that can be applied to medicine. Recently, there is a tendency to replace the traditional metal biomaterials such as austenitic steel or CoCrMo alloy by titanium alloys. Titanium alloys have good mechanical properties, low specific gravity and good corrosion resistance. Low specific gravity and high mechanical properties are especially important when a patient has more than one implant or when a surgeon operates with the surgical tools for a long time.

The most often applied implants are as following:

- implants applied to orthopaedic surgery and traumatology e.g. endoprostheses of hip and knee joints, intramedullary nails, stabilizers of the bone fracture, screws etc.,
- implants applied to facial and maxillofacial surgery,
- stomatology implants such as tooth implants, artificial denture, connection plates, orthodontic apparatus etc.,
- implants applied to cardiosurgery having direct contact with blood e.g. elements of artificial heart valves, casings of electrostimulators, adjunct systems of cardiac ventricle etc.,
- implants applied to laryngology e.g. in reconstruction of trachea,
- implants applied to ophthalmology.

The majority of implants are produced by the plastic working methods. Forging, rolling, stamping, drawing or punching are the technologies used the most often. Heat and surface treatments are also very important during the technological process of the implant production. Useable properties of the implants depend on the applied surface treatment significantly [6, 7].

Apart from the implants some surgical tools are also made from titanium alloys. Very often surgical instrumentarium cost surpasses the implant one so it is important that its durability will be long enough.

3. Plastic working of titanium alloys applying to the implants and surgical instruments

Deformability of titanium alloys depends on many factors such as: chemical composition, structure, temperature and strain velocity and also the way of deformation. The main factors, which make plastic working of titanium alloys difficult, are as following [8, 9, 10, 11]:

- susceptibility to creation of the build-ups on the tools (adhesive wear) and high friction coefficient,
- low thermal conductivity,
- high reactivity with gases (oxygen, nitrogen, hydrogen), especially in higher temperature.

Therefore parameters of deformation should be chosen respecting the process specificity.

3.1. Forging of titanium alloys

Forging of titanium and its alloys is the most common plastic working process applied to implant production. Forging is used to produce different kinds of endoprostheses stems, mainly stems of the hip, knee or elbow joints. The stem is the basic element of each joint endoprosthesis. Endoprosthesis stem transfers complex, variable in cycles mechanical loads for 10-15 years. Therefore, after many years' standing negative experiences with casting stems only forged stems are applied.

Forging process of Ti6Al4V titanium alloy takes place in the range of temperature 1000-800^{o}C. Both temperature and strain velocity have the essential influence on the properties of the forged elements. For the sake of high sensitivity to strain velocity, die forging of titanium alloys on the hydraulic presses is more suitable than on the hammers. In such case the alloys formability increases of about 10-12% [10, 11]. Low thermal conductivity of titanium alloys and high friction coefficient between the deformed metal and tool result in strain heterogeneity, which in turn, causes structure and properties heterogeneity.

A strong affinity with oxygen, nitrogen and hydrogen causes difficulties in hot forging of titanium alloys mainly Gaseous diffusion affects changes both in chemical constitution and microstructure of the product top layer. Such changes are unacceptable in the case of endoprostheses stems.

In order to secure the high quality of the forgings (endoprostheses stems) it is necessary to overcome three “technological barriers”:

- protection of the forging surface against gaseous diffusion during the heat process to the forging temperature,
- decrease in frictional resistance between the deformed metal and tool,
- application of the proper heat treatment (homogenizing treatment) after the forging process.

Therefore, heating of the slug forgings (rod) should be carried out with the proper protective atmosphere. During the forging process the proper technological lubricants should be applied. They play both protective and lubricating role.

3.2. Stamping of titanium alloys

Stamping is applied to produce some elements of the knee endoprostheses (e.g. clamping plates of the polyethylene inserts, condyle elements of the sled endoprostheses). Different casings such as casings of the artificial heart chamber, casings of the endoprostheses acetabular cups are also produced by stamping technology. Moreover, stamping is applied to produce some tools like forceps etc.

Figure 1 presents some examples of the products made by stamping technology.

Fig. 1. Some examples of the titanium products made by stamping technology [12, prospectus]

Titanium sheets applying for the drawn-parts should have the proper plastic properties (annealed state) and microstructure.

Sheet-titanium forming process can be carried out both in room and higher temperature (semi-hot forming). Temperature of 350-400^{o}C is the advised temperature to the semi-hot stamping (e.g. WT1-0 alloy). Sheet-titanium forming in higher temperature is applied in order to decrease the amount of operations and increase accuracy of the work.

Sheet-titanium forming process, especially of Ti6Al4V alloy, is much more difficult than sheet-steel forming process. The difficulty results from:

- high yield point and tensile strength,
- high strain hardening,
- high frictional resistance and susceptibility to creation of the titanium "build-ups" on the steel tool surface,
- high value of the Re/Rm ratio,

During the cold stamping processes it is necessary to apply intermediate annealing. In order to remove internal stresses the final products must undergo stress relief annealing. Both intermediate and stress relief annealing should be carried out with the protective atmosphere.

Limit drawing coefficient, m=d/D, is one of the criteria for judging sheet ability to deep drawing operations. During the cold stamping process of Ti6Al4V titanium alloy m=0,83÷0,76 while during the hot stamping process m=0,71÷0,63.

Strain velocity has an essential influence on sheet-titanium forming process, so it is advised to form titanium sheets on the hydraulic presses with the velocity lower than 0,25m/s. Corner radiuses and clearance between a punch and die are also very important.

In Figure 2 an influence of the lubrication and hardening layers on friction coefficient during sheet-titanium forming process has been shown. Friction coefficient has been determined in the "strip drawing" test.

According to the tests both lubrication and chromium layer sprayed on the tool cause a significant decrease in friction coefficient.

Lubrication should ensure the effective separation of the frictional surfaces, because during sheet-titanium forming process there is an intense creation of the "titanium build-ups" on the tool surface [8, 9]. In consequence scratches, which are impossible to remove in the following treatments, occur on a product surface. Figure 3, for example, shows changes in surface roughness in a "strip-drawing" test carried out for the tools with and without surfacing.

Not only does lubrication prevent from creation the "build-ups" on the tool surface but also makes easier the material flow resulting in strain uniformity and higher smoothness of surface.

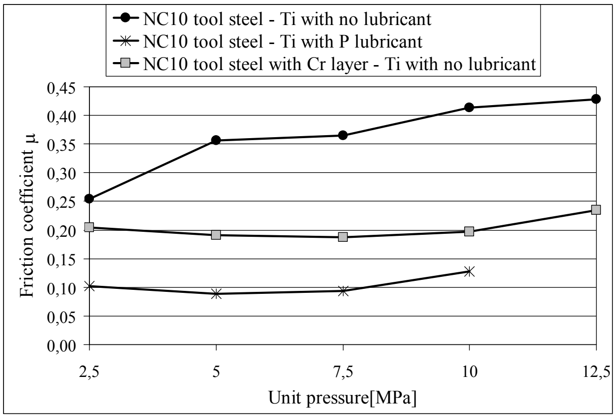

Fig. 2. Friction coefficient for the different frictional pairs

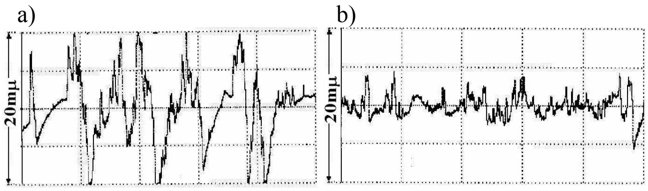

Fig. 3. Surface roughness - Ra parameter. Frictional pair: tool steel – titanium sheet a) tool surface with no layer, b) tool surface covered with Cr layer; friction distance 1m, unit pressure 10 MPa

3.3. Die shearing, restriking

Many elements of the implants and surgical instrumentarium are produced by the die shearing process. Cold-rolled annealed titanium sheets are the starting material. Than the blanks are shaped by restriking (mainly in order to obtain work hardening in the surface layer) and machining (drilling and milling the holes). After machining and restriking the implant surface are polished in order to obtain the required surface quality.

In this way such elements as: connection plates, self-locking plates, angular plates used in maxillofacial surgery and so on are produced. By die shearing, restriking and milling many different precise surgical tools (e.g. tweezers) are also produced.

Titanium sheets are mainly cut by conventional methods i.e. by two rigid cutting elements (a guillotine or a blanking tool). When surface appearance and dimensional accuracy are important alternative cutting methods, such as laser or abrasive waterjet cutting, are applied [14,15]. In contrast to conventional cutting, abrasive waterjet and laser cutting produce smooth edges which never need deburring. Moreover, laser and water cutting allow more optimal blanking and better material utilization, which is very important when expensive materials such as titanium sheets are shaped. However, it is necessary to emphasize that heat treatable materials, like β titanium alloys, become hardened at the cut edges during laser cutting. This may be beneficial if hardened edges are functionally desirable in the finished parts but if further machining operations such as flanging are required, then hardening poses a problem.

The microstructure of the titanium sheet, which was cut by guillotining, laser and abrasive waterjet method, observed under a metallographic microscope is shown in Figure 4.

The greatest change in material structure is observed for the titanium sample cut by guillotine (Fig. 4d). Clear elongation of the grains along the direction of the material flow is observed in the zone of the plastic strains, which affects material strain hardening. In the case of laser cutting a small heat-affected zone with larger grains than the grains in the rest of material appears (Fig. 4c). Only during abrasive waterjet cutting (Fig. 4b) is there no change in grain size – material structure is the same as for the initial material (Fig. 4a).

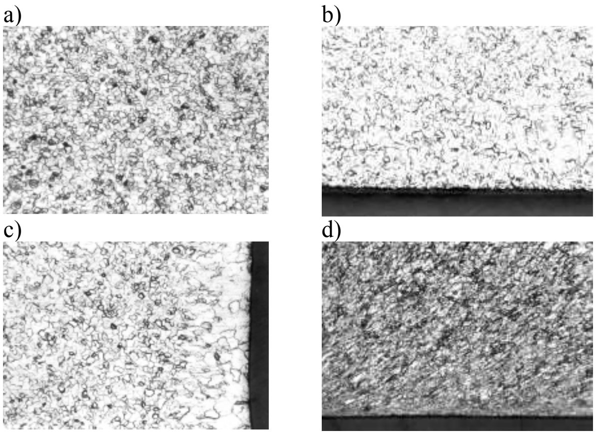

Fig. 4. Microstructure of WT1-0 titanium sheet: a) before cutting, b) after abrasive waterjet cutting, c) after laser cutting, d) after guillotining; metallographic microscope, magnification 100x

According to the test results the best quality of the cut-surface, taking into consideration both surface smoothness and the perpendicularity of the sidewall, was obtained by the laser cutting method. A less smooth surface but good perpendicularity of the side wall was obtained by the abrasive waterjet cutting. The burr for both the laser and abrasive waterjet cutting was minimal. The worst quality of the cut-surface was observed after guillotining. In this case the cut-surface is characterised by a large burr and significant sidewall batter.

4. Conclusions

- Plastic working is one of the leading technologies applying to production of the metallic implants in Biomedical Engineering.
- Application of the new biomaterials having high mechanical properties such as titanium alloys needs to carry on tests on optimisation of the methods and parameters of the plastic working.
- Technological lubricants or antiadhesive layers like Cr layer can limit or even completely eliminate the "build-up" phenomenon.
- Cut-surface quality significantly depends on the applied cutting method. The proper selection of the cutting method, in the case of titanium, should take into account the kind of material (α, β or α+β-titanium), the future function of the cut element and the manufacturing cost.

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