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Merjenje generacije toplote pri rezanju kosti z abrazivnim vodnim curkom

Heat Generation During Abrasive Water-Jet Osteotomies Measured by Thermocouples

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Abrazivni vodni curek (AVC) je v industriji znan kot hladni rezalni postopek, saj ne opazimo pomembnega toplotnega segrevanja na rezalnih robovih v primeru rezanja kovinskih materialov. Zaradi tega se AVC uporablja predvsem tam, kjer ne dovolimo toplotno prizadete cone v samem rezalnem materialu. Za medicinske uporabe je kritična temperatura dosti nižja kakor pri industrijski rabi, saj so kosti zelo občutljive za toploto. Poškodbe na tkivu so odvisne od same temperature v rezalni coni ter času rezanja. Tkivo se uniči že pri izpostavljanju za 10 sekund temperaturam, višjim od 57°C. Da bi se izognili temu učinku, tako imenovani nekrozi, ki povzroča slabše rasti kosti, je treba upoštevati temperaturo pri samem rezanju z AVC. Prvi koraki so narejeni v tem prispevku. Generacija toplote pri rezanju kosti z AVC je bila izmerjena z uporabo termoelementov, ki so bili vstavljeni v kortično votlino goveje kosti. Vplivi parametrov kakor so: tlak, rezalna hitrost, pretok abraziva, abrazivni material so prikazani v tem prispevku, prav tako tudi vplivi postavitve termoelementov.

(Ključne besede: medicina, rezanje kosti, curek vodni, curek abrazivni, meritve temperature, termočleni)

Water-jet technology is known in industry as a cold-cutting process because no significant thermal effects are observed at the cutting edges of, e.g., metallic workpieces. Thus, water jets are mostly used for applications where no structural changes are allowed. For medical applications the critical temperature is much lower than for industrial use, because bones react very sensitively to heat. The damage to the tissue depends on the temperature and the time of exposure. The tissue is irreversibly destroyed after a period of approximately 10 seconds at 57°C. To avoid this effect, which causes the so-called necrosis formation, and which results in poor bone healing, heat management is required for water-jet osteotomies. The first step is made in this paper. The heat generation during abrasive water-jet osteotomies was measured by thermocouples that were inserted into the cortical hollow bone segments of cattle. The influence of parameters like pressure, traverse rate, abrasive flow rate and abrasive material are shown in this paper together with the influence of the location of thermocouples, which represents an increment of the bone tissue.

(Keywords: medicine, osteotomy, abrasive water jet, temperature measurement, thermocouples)

0 INTRODUCTION

For orthopaedic surgery the standard method for cutting hard biological tissue like bones is still the use of mechanical tools like the oscillating saw [1]. However, bone reacts very sensitively to heat. Thermal damage to living tissue is related to the magnitude of the temperature and the exposure time [2].

Figure 1 shows the critical temperature with respect to the exposure time. When exceeding these limits, irreversible tissue damage occurs. Conventional tools, like saws and medical burs, generate temperatures of up to more than 100°C and cause, as a result, a layer of destroyed cells at the resection edges ([2] to [4]). These temperature traumas are responsible for a lack of bony ingrowths in prosthe-

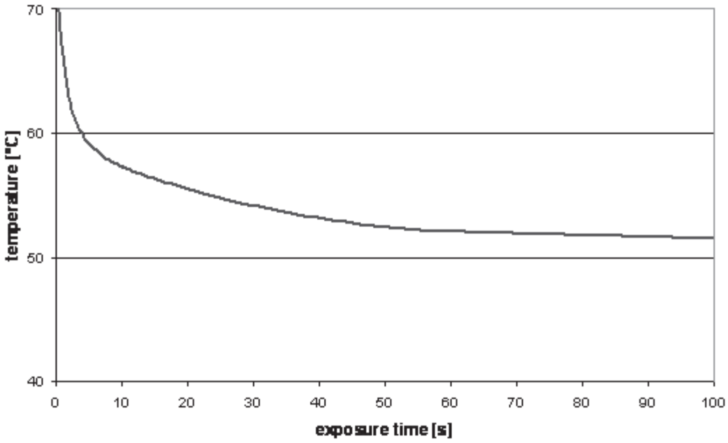

Fig. 1. *Necrosis formation of bone depending on the temperature and exposure time [2] and [3]*

ses and delayed bone-healing times ([3] and [4]).

For the last five years the research group from the Hannover Medical School, the Orthopaedic hospital Annastift, the University of Hannover and the University of Veterinary Medicine Hannover have investigated the possibility of introducing the water jet as a technique for medical applications. The feasibility of the abrasive water injection jet (AWIJ) as a tool for orthopaedic purposes, which can cut freely defined geometries with high accuracy, is already proven. The roughness is adjustable by choosing the parameters, and an average surface roughness of less than 20 µm can be realised [5]. Furthermore, the main focus in recent times has been the investigation of clinically usable abrasive materials. The requirements for abrasives that can be used for medical purposes, like biocompatibility and the biodegradability of the particles as well as the cutting performance obtainable with these abrasives, were examined ([6] and [7]). A major advantage of the AWIJ compared to the conventional bone-cutting tools seems to be that cutting with a water jet is a "cold cutting process". For pressure levels up to 100 MPa this has already been proven. The maximum temperature rise for this pressure was determined to be 13 K [8]. In-vivo studies of pigs have shown that this pressure is not sufficient when used in combination with a necessary new abrasive feeding system, with which the risk of embolism can be excluded [9]. Therefore, the pressure level for the AWIJ-Osteotomy has to be increased, and this is associated with an increase in the amount of transformed energy. Thus, a rise in temperature during the cut is assumed, which has to be screened.

The aim of this study is to investigate the heat generation during an AWIJ-osteotomy with re-

Fig. 2. *Preparation of the hollow bone segments (specimens)*

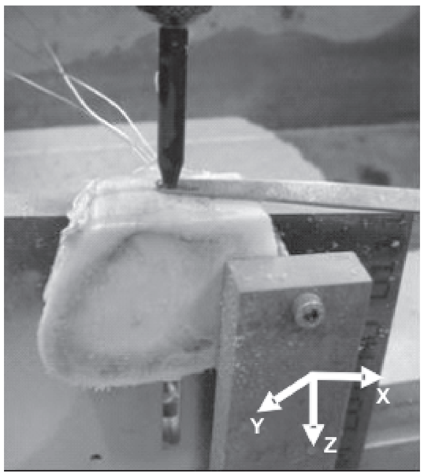

Fig. 3. *Fixation of the bone segments*

spect to parameters like pressure, abrasive flow rate, traverse rate and type of abrasive material.

1 MATERIALS AND METHODS

For this study hollow bones from the lower leg of cattle (bovine tibias) were used. The hollow bones were cut into segments with a band saw of approximately 2-cm thickness and then frozen at –32°C. The cortical thickness of the hollow bone segments varied between 4 and 14.8 mm. Before the AWIJ-cut, the segments were defrosted in saline solution at 37°C. An AWIJ-cut was performed to get a plain area on one side of the bone (see Figure 2). Afterwards, three bores were drilled in each cortical bone with a diameter of 0.6 mm. The depth of the bore was 6 mm ± 0.7 mm (the y-direction, see Figure 3). The distance between the three thermocouples was 1 mm for all measurements (the z-direction, see Figure 3).

Before inserting the thermocouples (type K, measurement range 0–1100°C, diameter 0.5 mm) the hole was filled with heat-conductive paste. Afterwards, the thermocouples were glued onto the bone with a hot sticking pistol to avoid any displacement during the cut. The sampling rate for the temperature was set to 0.1 s and the values were recorded using DasyLab Software.

The water-jet system consisted of an Uhde high-pressure intensifier (maximum pressure 400 MPa, maximum water-flow rate 4 l/min) and a 2-axis cutting table with a positioning accuracy of < 0.1 mm. The z-axis could be manipulated manually to set the stand-off distance. For this purpose the bone segment was fixed with the plain surface facing upwards. To measure the temperature of an AWIJ-cut with regard to the thermocouples' position a preliminary cut (in the x-direction) had to be conducted for each specimen to determine the cutting width. With this knowledge it was possible to cut directly in front of the thermocouples' head. A safety offset was set to 0.5 mm in the y-direction for all tests.

2 RESULTS

2.1 Influence of the thermocouples' location on the temperature

The thermocouples demonstrate an increment of bone tissue. Thus, with the experimental set up it was possible to check the temperatures of three bone increments with respect to a measurement period for each AWIJ-cut regarding their distance to the surface (z-direction) and regarding the distance of the cutting edge (see Figure 4).

The standard parameters were set as followed:

Abrasive material	Garnet
Pressure	300 MPa
Abrasive flow rate	6 g/s
Orifice/focus-diameter	0.25 / 0.8 mm
Traverse rate	100 mm/min

For all tests, the measured temperature is a maximum for the top thermocouple, which is placed directly on the bone surface. This is reasonable because it is a fact that the jet's energy decreases with the increasing depth of the cut. As a result less energy can be caused by friction.

In Figure 5 the measured maximum temperatures versus the distances of the thermocouples from

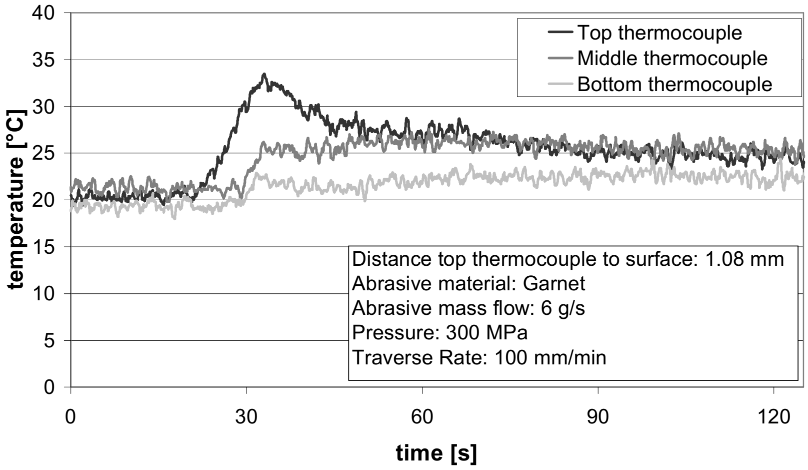

Fig. 4. *Example of a temperature measurement with three thermocouples*

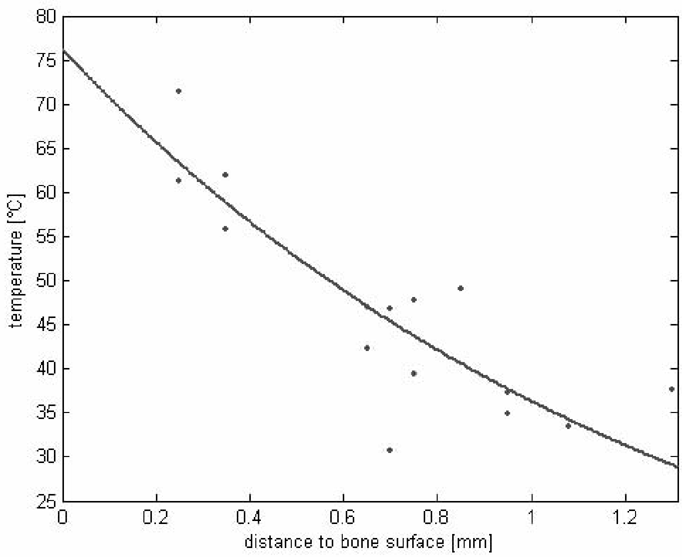

Fig. 5. *Temperature versus the distance of the thermocouples from the surface*

the surface for standard parameters are shown. Furthermore, an extrapolation of the measurement points based on a consideration of the least-squares method has been conducted.

It is obvious that the deeper the bone increment is placed, the less heat affects the cells during an AWIJ-osteotomy. Without a consideration of the exposure time, cell damage for a bony layer of a maximum of 1 mm thickness could occur during an AWJI-osteotomy (standard parameters), when assuming the critical temperature of 37°C.

2.2 Influence of different distances to the cutting edge on the temperature

To investigate the influence of bone increments that are not located directly at the cutting edge on the temperature, another parameter study was carried out. After a first cut at the specimen's border, the cut was shifted parallel in the direction of the thermocouple (the y-direction). Six cuts were performed until a distance of 1 mm between the thermocouple and the cutting edge was reached. The standard cutting parameters were used.

Figure 6 shows a mapping of the results. An association between the distance of the bone surface and the thermocouple and the temperature gradient can be seen. For increments of bone further inwards in the cortical bone, the temperature gradient is smaller than for increments that are directly at the surface. The reason is the influence of heat radiation at the surface.

2.3 Influence of the parameters on the temperature

The main point in this work was to investigate the influence of parameters like pressure, traverse rate and abrasive flow rate. The first step was to obtain general information about the parameters' influence on the temperature and exposure time. Therefore, the standard parameters were used, and each parameter was individually varied.

Figure 7 shows the results of the parameter study measured by a thermocouple that was placed 0.35 mm from the bone surface. It is obvious that the AWIJ with standard parameters does not cause any tissue damage during an AWIJ-osteotomy. The maximum temperature can still be decreased by lowering the pressure or the abrasive flow rate. When decreasing the traverse rate to generate a better surface quality of the cutting edges, a critical temperature and exposure time can be exceeded (e.g., standard parameters, but a traverse rate of 10 mm/min). Consequently, heat management, even for AWIJ-osteotomies, is required to completely avoid irreversible cell damage to the bone tissue.

2.4 Influence of different abrasive materials on the temperature

For medical applications it is not possible to use garnet as an abrasive material, because of a lack of biocompatibility and biodegradability [6, 7]. As a result, biocompatible abrasives were investigated and compared with respect to their impact on heat

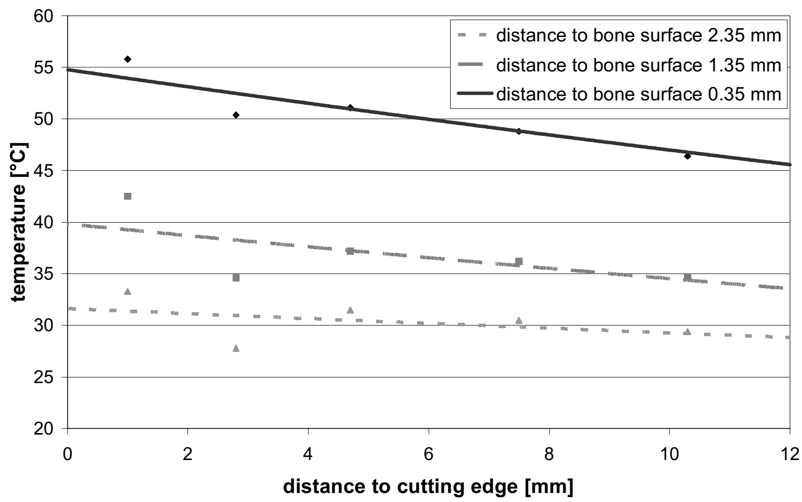

Fig. 6. *Temperature versus distance between the thermocouple and the cutting edge*

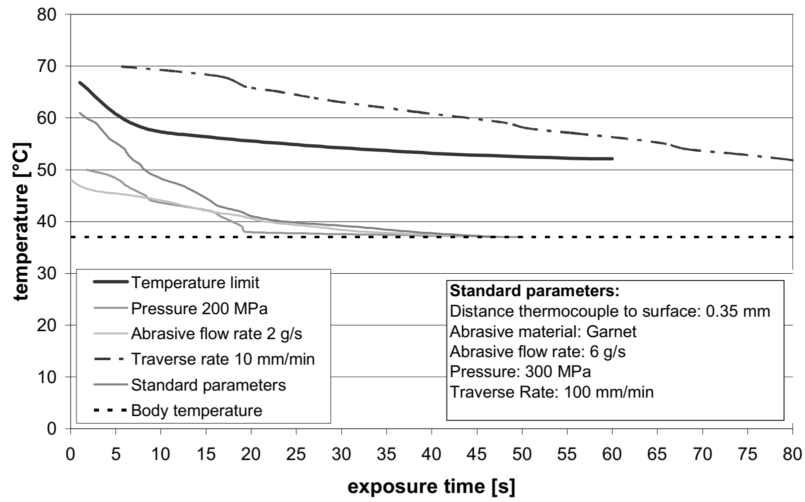

Fig. 7. *Effect of parameters on the temperature and the exposure time*

development during the AWIJ-cut. To secure the comparability of the abrasives' impact, the pressure was set to 350 MPa and the cutting performance of the different abrasives (magnesium, AZ91, sucrose and garnet) had to be similar. For this purpose the volume flow rate for all the abrasives was kept constant at 3.65 ml/s, according to the optimum (mass) flow rate of sucrose. The resulting abrasive (mass) flow rates are shown in Figure 8 (see inset).

To achieve an equal cutting performance of the different abrasives, the cutting depth in PVC depending on changes in the traverse rates was determined. Unfortunately, it was not possible to maintain the grain size distribution of the abrasives, which would also have an influence on the cutting performance. It is obvious that the biocompatible abrasives have a lower cutting performance than garnet for the same traverse rate. However, it is already known that the cutting ability of magnesium is superior to sucrose as an abrasive material [7]. The traverse rate for the influence comparison of the abrasive materials with respect to the temperature and exposure time was set according to the maximum traverse rate by using sucrose as the abrasive material to fully cut through a bovine tibia.

In Figure 9 the results of this abrasives' comparison are shown. It is clear that all of the tested abrasives do not cause cell damage, except for sucrose, using the given parameters. The problem is the bad cutting performance of the sucrose and, as a result, the necessity of a low traverse rate. Finally, it can be said that it is possible to avoid the irreversible damage of cells for all abrasives except sucrose for a bone layer below 0.35 mm.

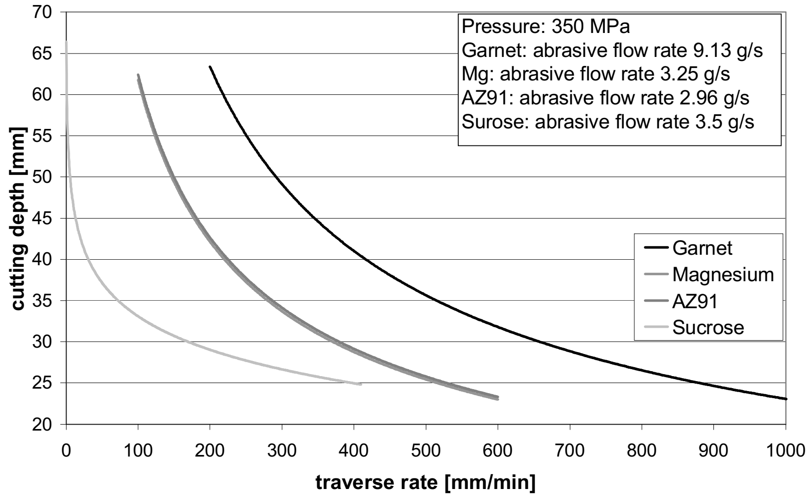

Fig. 8. *Cutting depth versus the traverse rate (specimen material PCV)*

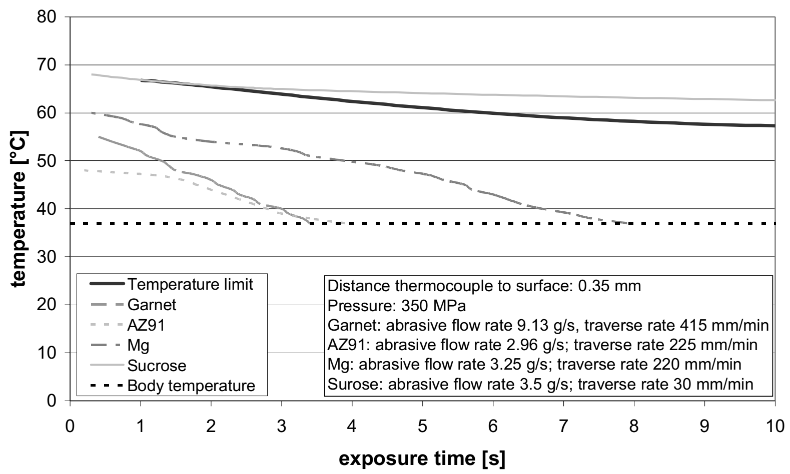

Fig. 9. *Temperature versus exposure time for different abrasive materials*

3 CONCLUSIONS AND OUTLOOK

With this presented study a further step to introduce the abrasive water injection jet for medical application has been made. It can be seen that it is possible to avoid bone-cell damage during osteotomies with the AWIJ by adjusting the parameters. In detail, a decrease in pressure and abrasive flow rate result in a lower temperature increase and a shorter exposure time to the critical temperatures. However, an increase in the traverse rate will have the opposite effect. With respect to an improvement in the surface quality of the cutting edges, by lowering the traverse rate the temperature increase has to be taken into consideration.

In addition, it has to be said that some factors have not been taken into account in this study. For further investigations the starting temperature of the bony specimens has to be increased to 37°C to reach comparable in-vivo conditions. The influence of the cortical bone thickness as well as the hardness, which differ for each bone, should be added into the evaluation of the results.

The aim of future investigations will be the determination of parameter limits to avoid cell damage, especially for biocompatible abrasives with respect to the new abrasive feeding system. This will make temperature management possible, whereby cell damage can be totally avoided by using the AWIJ for medical purposes.

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