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An experimental study of bushing formation during friction drilling of titanium grade 2 for medical applications

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Abstract. Recent advances towards patient specific, Titanium sheet based medical implants introduce a new challenge for the fixation of these implants to bones. Mainly the use of locking screws requires an implant thickness of approximately 2 mm for screw thread formation. Friction drilling is a hole-making process that displaces material to create a bushing below the sheet rather than extracting material. Screw thread can be formed in this bushing for the medical locking screws. This experimental study explores the influence of axial force, rotational speed and workpiece temperature on the bushing formation during friction drilling of Titanium grade 2 sheets. Finally, the influence of the optimal parameters on the material hardness is characterized.

Introduction

The shift towards patient tailored medical care has been tangible in the advances made in research towards patient specific plate osteosynthesis. Vancleef et al [1] have studied the potential of custom thin-walled implants for clavicle bone reconstruction. Benefits were identified on improved anatomical alignment of bone fragments, due to a better fit, while the reduced implant thickness results in less soft tissue irritation. Although thin-walled implants can reduce irritation and eliminate a potential secondary operation for implant removal, a reduced plate thickness poses a challenge towards plate fixation. While conventional osteosynthesis screws are countersunk in the implant, locking head screws use a threaded head to create angular stability to the bone fragments (Fig. 1).

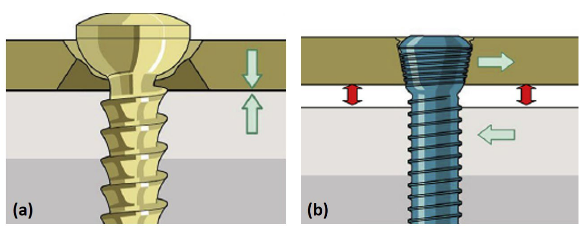

Fig. 1. Medical implant fixation through (a) conventional screws, (b) locking screws [2].

Commercial osteosynthesis locking screws have a head height of approximately 2 mm fitting the current commercial clavicle plates with a thickness varying from 2.3 to 3.4 mm. Vancleef et al [1] have shown, however, that patient specific plates of 1.5mm average thickness suffice to bear the loads acting on the broken bone. Thinner plates with varying thickness throughout the plate, even down to 1mm, are subject of ongoing research.

Friction drilling, a chip-less hole making process, provides an interesting solution to increase plate thickness at the fixation points. The process deforms the workpiece material through friction between the conical rotating tool and the sheet, instead of removing it. The resulting upwards

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formed boss and downwards formed bushing can have a combined height up to four times the initial sheet thickness [3].

This process was first proposed/described in 1923 by Jan Clause de Valliere but could only be put into practice 60 years later through the development of Tungsten Carbide (TC) tools.[4]. Since the first experiments, research has been focusing on improving the emerging geometry of bushing and hole through optimizing process parameters. More specifically the bushing quality can be quantified by its height and thickness and occurrence of cracks and petal formation. Ozler et al. [5] concluded that an increased *rotational speed* of the drill (ω) increases the temperature and thus lowers the yield stress, resulting in a lower thrust force. A longer bushing height is accompanied by a thinner bushing and reduced petal formation as a result of the increased forming temperature.

Most research has been performed using a constant *feed rate* (*f*), letting the thrust force vary throughout the different stages of friction drilling a hole [6]. The contact time between drill and sheet reduces with increased feed rate, resulting in a higher thrust force and tool torque. An increased roughness, shortened but thicker bushing and increased petal formation and cracks are the main effects on the final hole. [6]. The presented work uses a *constant thrust force* and thus the forming speed varies as the drill sinks through the sheet.

Friction drilling Titanium is associated with multiple challenges due to its low thermal conductivity and high chemical reactivity. Isolating and accumulating the temperature in the tool/sheet contact zone results in local melting and extreme long and thin bushings [7]. The high workpiece temperature in an oxygen rich environment results in the formation of Titanium oxides which drastically increases drill wear through adhesion and abrasion[3]. This publication will introduce *workpiece pre-heating* for Titanium grade 2, in order to reduce the temperature gradient throughout the sheet and the required heat flux, generated by friction, for plastic bush formation. A more uniform heating eases the superplastic deformation of the material from the sheet into the bushing.

Material and methods

Titanium grade 2 of 1mm thickness is chosen as workpiece material. It is the most used commercially pure Titanium for medical applications due to its excellent strength to weight ratio, biocompatibility, lack of magnetic attraction and wide availability.

Table 1. Properties of Titanium grade 2.

Density [Kg/m³]	4510
Youngs modulus [GPa]	100 - 105
Yield strength [MPa]	276 – 400
Hardness, Vickers [HV]	145 – 165
Thermal Conductivity [W/(mK)]	16 – 18
Melting Point [°C]	1670

A 3.7mm friction drill (Flowdrill M04 – 3.7 Long standard) has been used. It is made of tungsten carbide in cobalt matrix and has a friction angle of 36°. Berulit 935, is selected as lubricant for its high temperature stability, in order to reduce tool wear. It is applied to the tool prior to forming of each hole. Moreover, the drill is also cleaned after each use with a steel wire brush to remove Titanium adhesion to the tool.

Drilling is performed on an Alzmetal Drill press which allows a wide variety of rotation speeds. It is equipped with an actuation disk that allows to attach different weights to provide a constant thrust force on the drill. Fig. 2 depicts the experimental platform.

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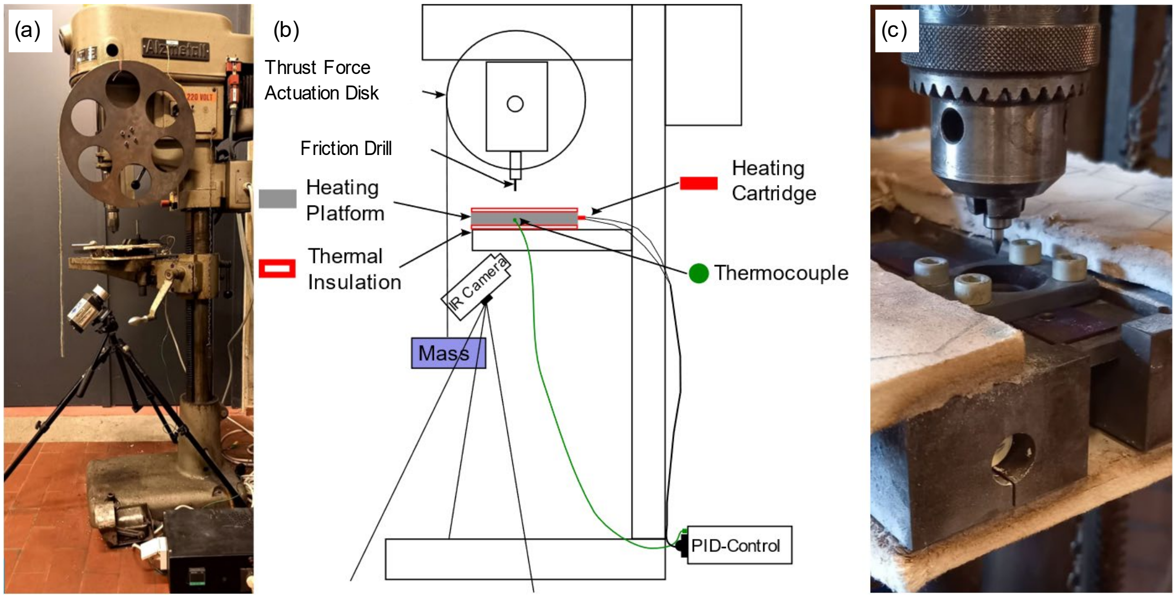

Fig. 2. (a) Lab setup and (b) Schematic representation of the friction drilling platform (c) Closeup of the friction drill and heating platform.

A custom made heating platform has been mounted on the bed of the table drill in order to pre-heat the Titanium sheet. The platform is manufactured from S235 JR and is heated by two Vulstar 1007-26 cartridge heaters. Applying a thermal paste between the platform and heating elements ensures that no air gap is present. Insulation layers are applied at the top and bottom of the platform to prevent the heat from flowing to the machine. Due to the high thermal inertia, the block is kept at constant temperature throughout tests using a PID controller receiving temperature feedback by a K-type thermocouple. Interchangable steel clamping plates, with a low thermal capacity, are used to clamp the Titanium sheet and can be mounted on the steel heating platform. Fig. 3 shows a CAD drawing of the heating platform. An 8mm hole in the clamping plate allows space for the drill to penetrate through the sheet while the plate acts as support of the sheet to localise plastic deformation.

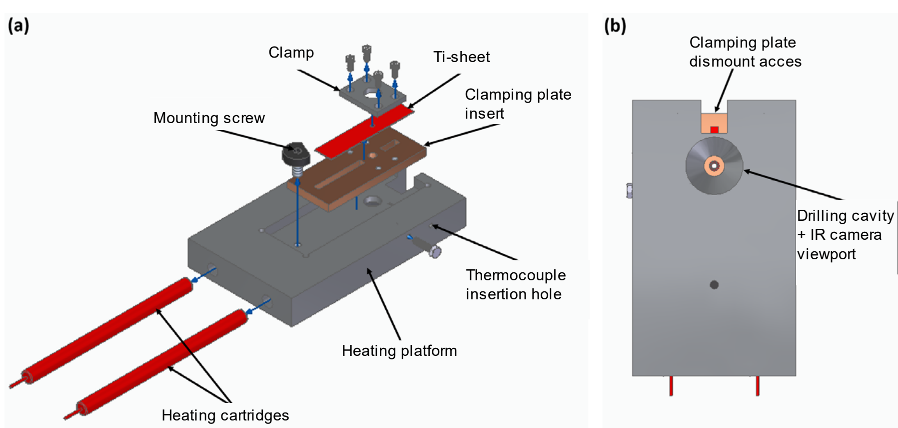

Fig. 3. CAD drawing of the heating platform: (a) Exploded view, (b) Bottom view.

Besides a thermocouple to control the heating block temperature, a FLIR Thermovision A20m IR camera is set up to monitor the backside of the sheet for temperature verification. A secondary thermocouple on the front of the sheet is used to verify the preheating temperature.

The bushings are analyzed using a Nikon LC 60 Dx laser scanning probe, mounted on a Coord3 CMM. The resulting point clouds allow to measure the bushing height and thickness. The total hole length, which corresponds to the useful length for thread cutting, is defined as the bushing height + the 1mm thickness of the Titanium grade 2 sheet, as described in the materials section. The thickness measurement is performed at 1mm from the back of the sheet, thus at a 1mm bushing height. As possible cracks or petal formation cause variation of height and thickness along the circumference of the bushing, the bushing height is defined as the minimum crack-less height measured. The thickness is defined as an average thickness taken along the circumference of the 1mm mark for the remainder of this paper (Fig. 4).

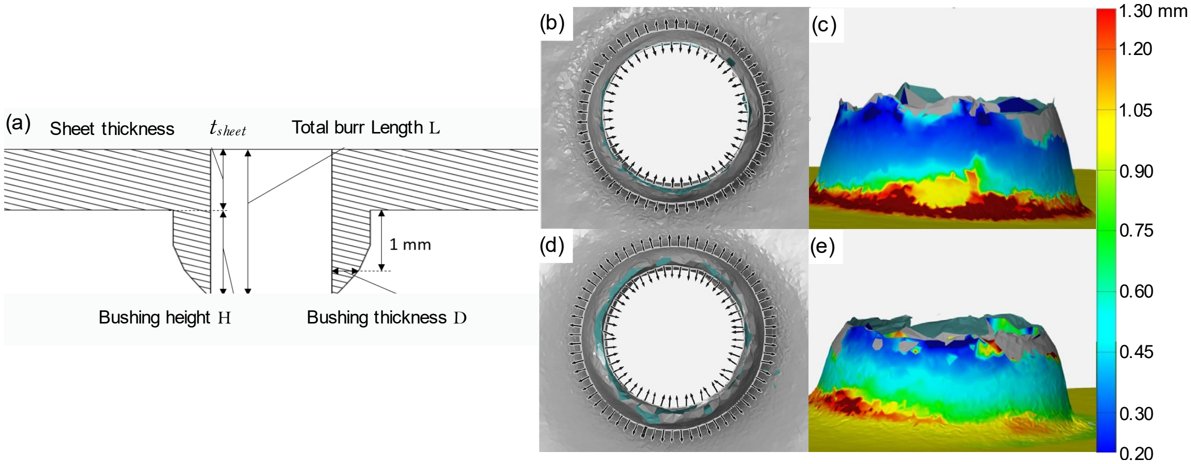

Fig. 4. (a) Dimensions nomenclature for friction drilling in this paper, (b & c) Thickness measurement of cold friction drilled hole, (d & e) Thickness measurement of pre-heated friction drilled hole.

The formed bushing is used to contain and stabilize locking screws used during operations. This requires the bushing to be strong, but still ductile enough to form the thread using roll tapping. Micro hardness measurements have been performed along the cross section of the friction drilled hole. First the workpiece is cut in half by means of wire electrical discharge machining. After embedding and polishing, a Shimadzu HMV-2000 micro hardness measuring platform is used with 500gram of weight for indentation. Fig. 5 shows the indent locations along the bushing and the sheet surrounding the hole. A total of five indents have been made for each sample respecting the proper distance from the side as well as from each other. The indents are measured using a Hirox KH-8700 digital microscope.

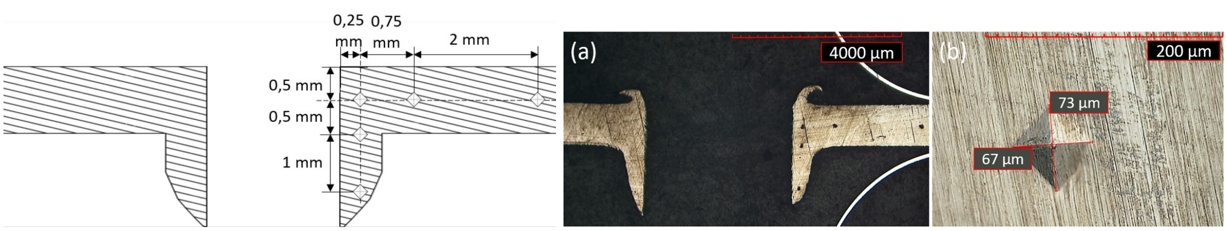

Fig. 5. (a) Locations of indents for hardness measurements, (b) Close-up of an indent.

The thrust force, rotational speed and workpiece pre-heating temperature are considered in a factorial analysis varying between two levels. The thrust force is limited on the lower side by a lack of penetration while the upper boundary is defined by premature breakage of the bushing. Both cases are most stringent limited when no pre-heating is used. Analogously, a lack of penetration through lack of heat defines the bottom limit of the rotational speed. The upper limit here however is constrained by machine capacity. The table drill used for the experiments has a maximum rotation speed of 2800rpm. Finally, the lower- and upper limit for the variable workpiece pre-heating are respectively the room temperature (20°C) and the highest stable temperature the described setup can achieve (525°C). Table 2 summarizes the input parameters for the factorial analysis.

Table 2 variable levels for factorial analysis

	Low	High
Thrust force [N]	361	722
Rotational speed [rpm]	1400	2800
Temperature [°C]	20	525

Results and discussion

The factorial analysis focusses on the total hole length, cracks and bushing thickness as responses. A minimal total crack-less hole length of 2mm is envisioned in order to contain the total locking screw head. Longer bushings are acceptable as they can be ground down to the correct length. The thickness should however be as large as possible for structural purposes.

All experiments were performed 5 times and had a minimal bushing height (Hmin) of 1mm, resulting in a total hole length exceeding 2mm. The interval plot in Fig. 6 depicts a 95% confidence interval for the minimal bushing height. A trend of increasing bushing height can be observed with increasing rotational speed and increasing workpiece pre-heating temperature. Both will increase the final total workpiece temperature, improving superplasticity. The effect of increased thrust force is however less obvious as rising the thrust force increases the occurrence of cracks. A higher thrust force also increases the forming speed and lowers the superplastic effect.

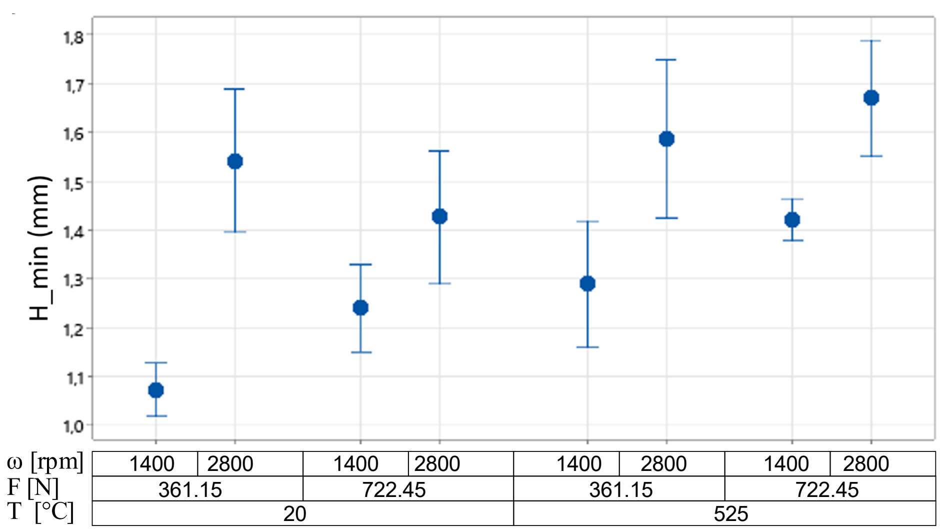

Fig. 6. Interval plot of the minimal bushing height.

As all experiments fit the requirement of minimal 1mm bushing height, the thickness can be analysed using Minitab. The Pareto graph shown in Fig. 7 shows the thrust force (F) as most significant variable for determining the bushing thickness. It is followed by the workpiece pre-heating temperature (T), the temperature interaction-thrust force (T·F) and rotational speed (ω). The thrust force-rotational speed interaction barely crosses the significance line, while other interactions are deemed not significant.

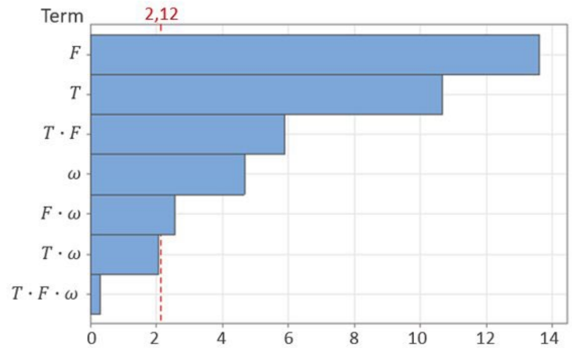

Fig. 7. Pareto chart of the standardized effects for the bushing thickness.

An analysis of the significant effects shows a considerable increase in bushing thickness when increasing the workpiece pre-heating temperature. This was expected as pre-heating the sheet reduces the temperature gradient and aids in increasing the volume of material at elevated temperature, which is thus subjected to superplastic forming. An increase of thrust force also has a beneficial effect on the bushing thickness and follows earlier observations described in literature [5], where an increased feed rate (and accompanying thrust force) resulted in thicker bushings due to the increased radial force applied on the material. This, however, also causes shorter bushings and an increased probability of crack formation as negative side effects. The rotational speed has a reducing effect on the bushing thickness due to increased temperature, which results in an increased material flow into a longer bushing, at the cost of bushing thickness.

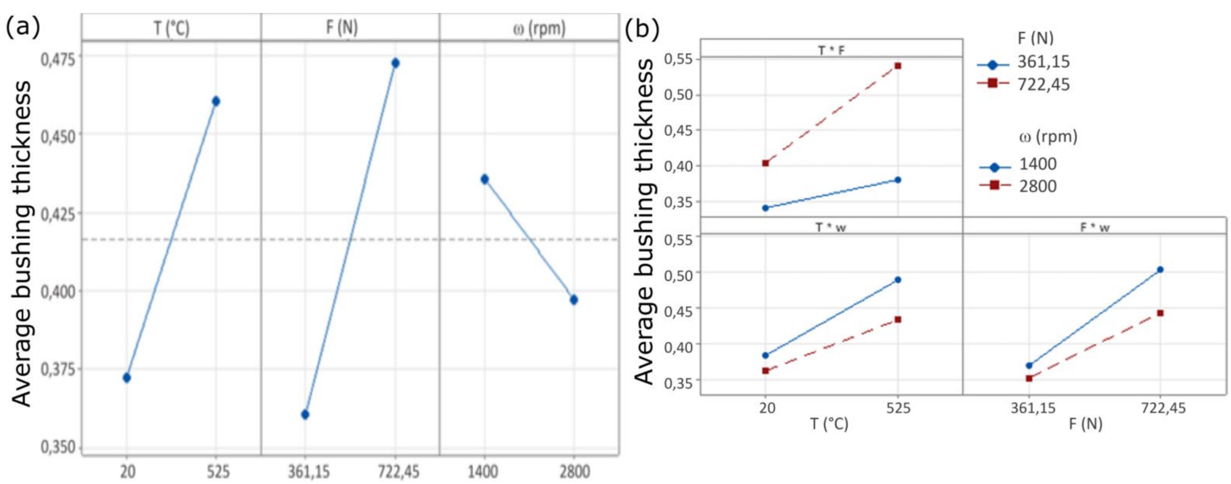

Fig. 8. (a) Main effects and (b) 2nd order interaction effects for bushing thickness.

Fig. 8b shows a clear interaction between workpiece pre-heating and thrust force. The effect of temperature increase is much more pronounced at high thrust force than at low thrust force. This again confirms the effect on bushing thickness of involving more material in the plastic deformation. Fig. 4 shows the difference in bushing thickness between room temperature and pre-heated workpiece material.

A reverse and reduced interaction can be seen for T·ω and F·ω. In these cases the effect of workpiece pre-heating and thrust force respectively are reduced when the rotational speed is increased.

Hardness measurements for the bushings and surrounding of the friction drilled holes were performed on bushings made with and without pre-heating of the workpiece. The parameters used are summarized in Table 2.

Table 2. Parameters for pre-heated and room temperature friction drilling targeting maximal bushing thickness.

	Pre-heated	Room temperature
Temperature [°C]	535	20
Thrust force [N]	1017	722
Rotational speed [rpm]	1400	1400

Fig. 5 shows the five different measurement locations along the cross section of the sheet. Three along the horizontal axis and three along the bushing, sharing the corner location. Each test was performed at least 5 times of which the average is depicted in Fig. 9. The intervals represent the 95 confidence interval for these values. As discussed in the material section, the reference values for the hardness of Titanium grade 2 is 166-165HV. This matches the values obtained 3mm away from the drilled hole. The measured hardness increases when moving closer to the hole and the heat affected zone. A more linear increase is observed in the pre-heated samples as compared to the exponential profile seen in the room temperature samples.

The hardness along the bushing shows a similar evolution between pre-heated and non-pre-heated samples. In both cases the measured hardness was higher at the 1mm location than in the 0.5mm corner point and the 2mm point, further down the bushing. The cold formed bushings have a higher hardness over the entire bushing compared to the pre-heated ones.

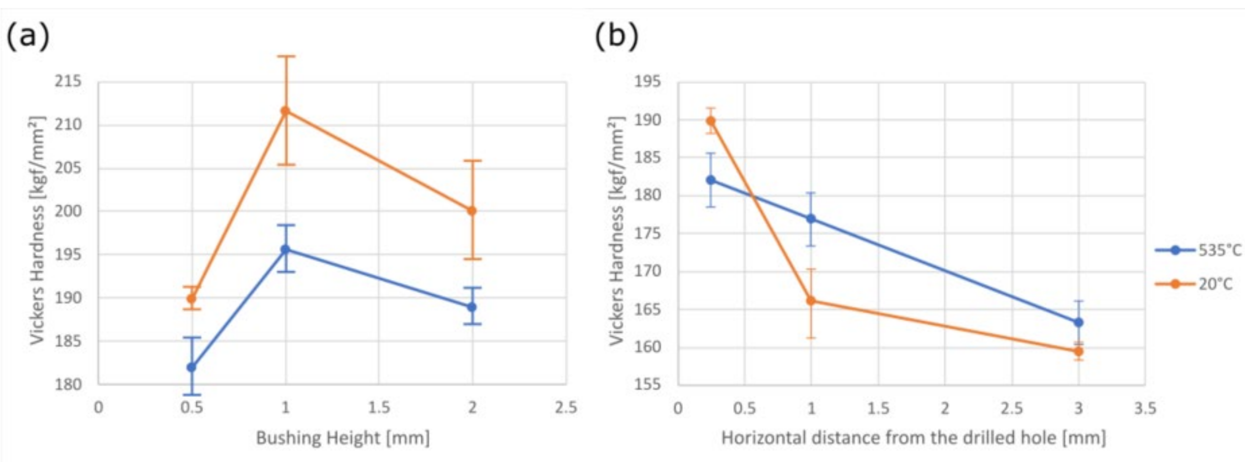

Fig. 9. Vickers hardness profile (a) along the created bushing, (b) along the undeformed sheet.

Conclusion and future work

This paper summarizes an explorative study on the influence of rotational speed, thrust force and pre-heating on the bushing formation in friction drilling of grade 2 Titanium. It has been shown that the use of pre-heating has a positive influence on both bushing height as well as bushing thickness. An increased thrust force mainly has a varying effect on the crack free bushing height due to increased occurrence of cracks. It is however, beneficial for the bushing thickness. Increasing the rotation speed induces more heat into the sheet tool contact zone, resulting in higher but thinner bushings for Titanium grade 2. Finally, a comparison is made between the hardness of a workpiece formed at room temperature and pre-heated conditions, where forming at room temperature results in a higher hardness. Future work will focus on the mechanical characterisation of the bushings, thread cut into them and strength and stiffness of the connection with the medical locking screws.

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