KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

ANALYSIS OF COMPACT BONE VIBRATION ASSISTED DRILLING

Final project for Master degree

Mechatronics study programme (code 621H73001)

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KAUNAS, 2015

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ANALYSIS OF COMPACT BONE VIBRATION ASSISTED DRILLING

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2015 May 12
Kaunas

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Zakrasas, R. Analysis of compact bone vibration assisted drilling. *Master of Mechatronics* final project / supervisor Assoc. Prof. Dr. Jolanta Baskutienė; Kaunas University of Technology, Mechanical engineering and design faculty, Department of Production Engineering.

Kaunas, 2015. 52 p.

SUMMARY

Bone drilling is one of the most often done orthopaedic procedures and because it is done by hand more times than not surgeons are not able to achieve best drilling performance. As a result, temperatures above recommended may be observed at the drill-bone interface, which leads to necrosis of the bone and in turn to longer healing time. To decrease drilling temperature it was proposed to utilize low frequency assisted drilling, as it showed great results when drilling various difficult to machine brittle and hard materials as well as various laminated composites.

Two experiments were designed and performed to analyse effect vibration assisted drilling has on the drilling temperature of PMMA, and bone samples. Temperature at the exit hole was measured with thermal camera, it was noted as the drilling temperature. Between drilling operations drill rotational speed, applied force, drill bit parameters, sample properties were taken as constant. Vibration frequency and amplitude were the only varied parameters.

Even though the obtained data shows that vibration assisted drilling reduces drilling temperatures, it is important to take into account the limitations of experimental setup. This investigation of vibration assisted drilling of compact bone should be thought of as a stepping stone for future research.

SANTRAUKA

Kaulų gręžimas yra viena iš dažniausiai atliekamų chirurginių ortopedinių procedūrų, tačiau gydytojams ne visada pavyksta pasiekti geriausias gręžimo sąlygas, nes temperatūros viršija saugias. Pagrindinė per aukštos kaulo gręžimo temperatūros komplikacija yra ilgesnis gijimas. Siekiant sumažinti gręžimo temperatūrą buvo pasiūlyta naudoti vibracinio gręžimo metodą, kuris, leidžia pasiekti geras gręžimo savybes, dirbant su trapiomis, kietomis ar kompozitinėmis medžiagomis.

Norint išsiaiškinti, kokį efektą vibracinis gręžimas turi PMMA ir kaulu gręžimo temperatūrai, buvo sukurti ir atlikti du eksperimentai. Temperatūra juose buvo matuojama termografine kamera, tuo momentu, kai grąžtas pergręžia bandinį, ši temperatūra yra laikoma gręžimo temperatūra. Atliekant bandymus gręžtuvo sukimosi greitis, naudota spaudimo jėga, grąžto bei bandinių parametrai buvo laikomi pastovūs, tiktai pagalbinės vibracijos dažnis ir amplitudė buvo kintami parametrai.

Eksperimento metu gauti duomenys parodė, jog vibracinis gręžimas iš tiesų pasižymi mažesnėmis gręžimo temperatūromis. Suformuluotose išvadose apžvelgiami eksperimento privalumai ir trūkumai, pateikiamos galimos tobulinimo kryptys.

KAUNAS UN IVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:
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Production Engineering
Department

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(Signature, date)

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(Name, Surname)

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHATRONICS

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

ANALYSIS OF COMPACT BONE VIBRATION ASSISTED DRILLING

Approved by the Dean 2015 y. May m. 11d. Order No. ST17-F-11-2

2. Aim of the project

The aim of the project is to design and conduct an experiment on thermal properties of vibration-assisted drilling

3. Structure of the project

Introduction Literature review Design of experiment Analysis of experimental data Conclusions

4. Requirements and conditions

Drill bit: Material – HSS, Diameter - 4.2 mm, Point angle – 120 Drilling speed - 1200 rpm, Applied force ~ 30N, Low-frequency vibration drilling frequency range 60Hz - 120Hz, Materials – PMMA, bovine bone

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student _______________________

Task Assignment received _______________________ _______________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor _______________________ _______________________
(*Position, Name, Surname*) (*Signature, date*)

TURINYS / CONTENT

LIST OF TABLES AND FIG.S

Tables:

Fig.s:

Fig. 22 Bone drilling a) Temperature dependency on vibration mode b) Time dependency on vibration mode

Fig. 23 Improvement of cutting parameters in the given vibration modes

Fig. 24 Highest observed temperature a) Hole b) Chip

Fig. 25 Accelerometer readings (peak-to-peak 60mV)

LIST OF ABREVIATIONS

CD – Conventional drilling

VAD – Vibration assisted drilling

UAD – Ultrasonically assisted drilling

USM – Ultrasonic machining

PMMA – Poly (methyl methacrylate) also known as Acrylic, Plexiglas

IR – Infrared

INTRODUCTION

Various orthopedic procedures are done thousands of times every single day. Every time someone has a fracture that cannot be healed using casts and splints, some sort of internal or external fixation method is used. To have supporting plates connected to the bone, holes need to be made.

Bone drilling is one of the most often done orthopedic procedures as it is done by hand more times than not surgeons are not able to achieve optimal drilling performance. As a result, temperatures above recommended may be observed at the drill-bone interface, which leads to necrosis of the bone and in turn to longer healing time [1]. Over the years some progress has been made in identifying the main culprits of unwanted temperature rise and some novel solutions to fight it. In the forefront is vibration assisted drilling, as it lowers the temperatures significantly without the need to precisely control other drilling parameters [2].

This paper is divided into three main parts, part 1 deals with theoretical background behind bone drilling, part 2 is for the design of the experiment that indicates the effect vibration assisted drilling has on the bone, and finally in part 3 the results are discussed.

The aim of this thesis is to design and conduct an experiment on thermal properties of vibration-assisted drilling, which is achieved by completing these tasks:

1. Study of the main parameters that influence the quality of bone drilling;
2. Review of the literature regarding vibration assisted drilling;
3. Selection of viable experiment parameters;
4. Design and execution of experiment;
5. Analysis of the obtained data.

1. VIBRATION ASSISTED DRILLING

This section is a brief overview of bone drilling parameters and their implications to health of the bone.

1.1 Bone drilling

Bone drilling is associated with the conversion of mechanical work energy into thermal energy causing a transient rise in temperature of adjacent bone and soft tissues to above normal physiological levels. Primary sources of this thermal energy are plastic deformation and shear failure of bone and friction at the machining face. The magnitude of this temperature rise is determined by a number of factors, including drill geometry and diameter, rotational speed (rpm), feed-rate (mm/s), axial thrust force (N), initial drill-bit temperature and internal or external cooling [1]. It is known that an excessive rise in temperature around a drill-hole will cause thermal necrosis of bone, and it has been shown that temperatures of over 50°C are associated with irreversible changes in the structure and physical properties of bone [3].

Table 1 Bone mechanical properties

Property	Thighbone (femur)	PMMA (bone cement)
Density, g/cm^3	1.6-1.7	1.1-1.2
Youngs modulus, GPa	10-15	1-3
Tensile strength, MPa	90-130	30-70
Compressive str., MPa	130-200	80-120
Fracture strain, %	1-3	0.1-0.3
Toughness, $MPa{\cdot}m^{1/2}$	1-2	1-3
Hardness (Vickers)	50-100	50-100

Bone is a nonhomogeneous composite material with hard compact bone on the outside and soft porous bone on the inside, and although there are other materials that may be mechanically superior, bone is unique for its capacity for self-repair and adaptation. Bone's elastic modulus – its stiffness during elastic deformation – spans 15-25 GPa, roughly a third of metallic aluminum; its strength, the applied stressed onset of plastic deformation, is a few hundred MPa, comparable with alumina ceramics; and its fracture toughness, a measure of material's resistance to fracture, is typically 3-10 MPa/m some 6 to 10 as high as silicon [7].

PMMA (acrylic, Plexiglas) is said to have similar properties to human bone, **Table 1** shows how it is comparable to human femur. It has been suggested in [3], [4], that for experimental purposes and an increased repeatability, instead of bone this synthetic material could be used.

Bovine bone also has properties comparable to that of human bone [5], [6]. It is most often used in various experimental setups where it is of utter importance to have conditions similar to those that appear in living human beeings.

1.1.1 Internal fixation

Bone, or osseous tissue, supports and protects body structures, it also provides cavities for storing fat and synthesizing blood cells. Bone matrix is similar to that of cartilage but is harder and more rigid because, in addition to its more abundant collagen fibers, bone has an added matrix element – inorganic calcium salts [5]. Thus once the load exceeds the capacity of the bone, the fracture occurs. The body then initiates bone repair and the reconstruction process in order to restore bone functional properties. When bone fractures, it must be stabilized immediately until it is strong enough to manage the weight of the body.

Until the last century, physicians relied on casts and splints to support and stabilize the bone from outside the body. The advent of sterile surgical procedures reduced the risk of infection, allowing doctors to internally set and stabilize fractured bones. During a surgical procedure to set a fracture, the bone fragments are first repositioned (reduced) into their normal alignment. They are held together with special implants, such as plates, screws, nails and wires.

Internal fixation allows shorter hospital stays, enables patients to return to function earlier, and reduces the incidence of nonunion (improper healing) and malunion (healing in improper position), of broken bones. The implants used for internal fixation are made from stainless steel and titanium, which are durable and strong. If a joint is to be replaced, rather than fixed, these implants can also be made of cobalt and chrome [6].

1.1.2 Bone classification

Bones are classified according to shape, structure and a variety surface features. All 206 major bones in a typical adult human can be divided into four broad categories [8]:

Flat bones have thin, nearly parallel surfaces. Flat bones form the roof of the skull, the sternum, the ribs, and the scapulae. They protect underlying soft tissues and have an extensive surface area for the attachment of skeletal muscles Fig. 1 a).

Long bones are relatively long and slender. They are located in the arm and forearm, thigh and leg, palms, soles, fingers, and toes. The femur, the long bone of the thigh, is the largest and heaviest bone in the body **Fig. 1** b).

Irregular bones have complex shapes with short, flat, notched, or ridged surfaces. The spinal vertebrae, the bones of the pelvis, and several skull bones are irregular bones **Fig. 1** c).

Short bones are small and boxy. Examples of short bones include bones in the wrists (carpal bones) and in the ankles (tarsal bones) **Fig. 1** d).

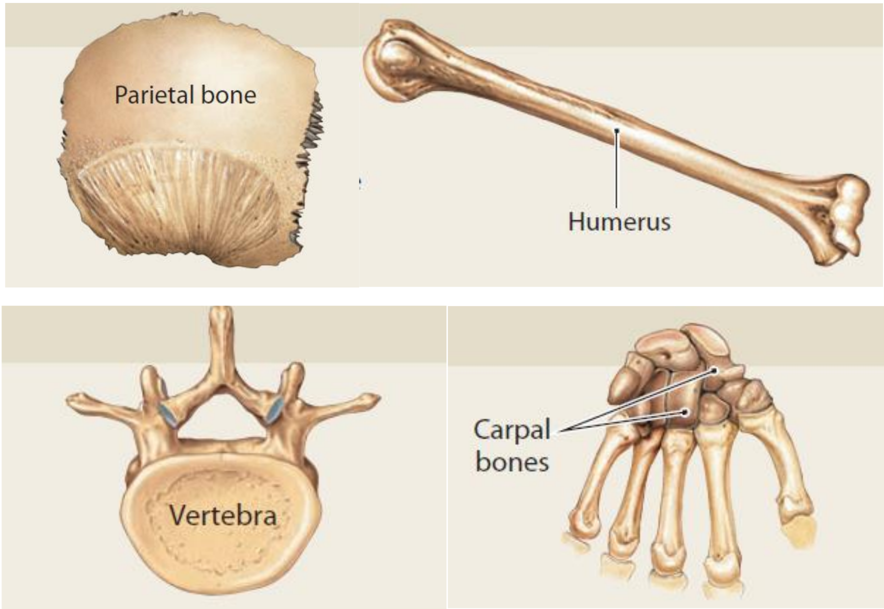


Fig. 1 a) Flat bone; b) Long bone; c) Irregular bone; d) Short bone [8].

Long bones have four main functions. The first function is structural. Bones provide the shape for our bodies and host vital organs. Body locomotion is the second function of the bone. The complicated kinematic skeletal system enables movement, using muscles that control bone positions and orientations. Bones transmit loads and act as levers. Joints are the fulcrums about which bones move. Therefore, the prime qualities of bones are strength and rigidity [9]. As can be seen in **Fig. 2** long bones are made of very dense cortical bone on the outside (**Fig. 3** a)) and very porous, spongy bone inside (**Fig. 3** b)). The marrow cavity is a space within the hollow shaft. In life, it is filled with bone marrow, a highly vascular tissue. The epiphysis consists largely of spongy bone. Spongy bone is an open network of struts and plates that resembles latticework. Except within joint cavities, spongy bone has a thin covering of compact bone.

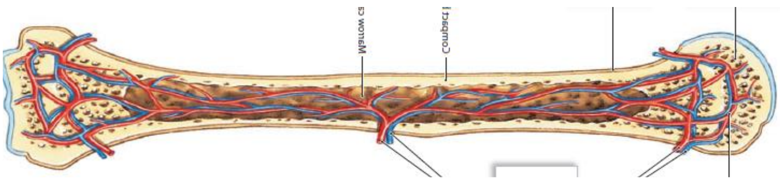


Fig. 2 Long bone [8]

The superficial layer of compact bone is wrapped by a sheath of connective tissue, called the periosteum, which (1) isolates the bone from surrounding tissues, (2) provides a route for blood and nerves, and (3) plays a role in bone growth and repair [8].

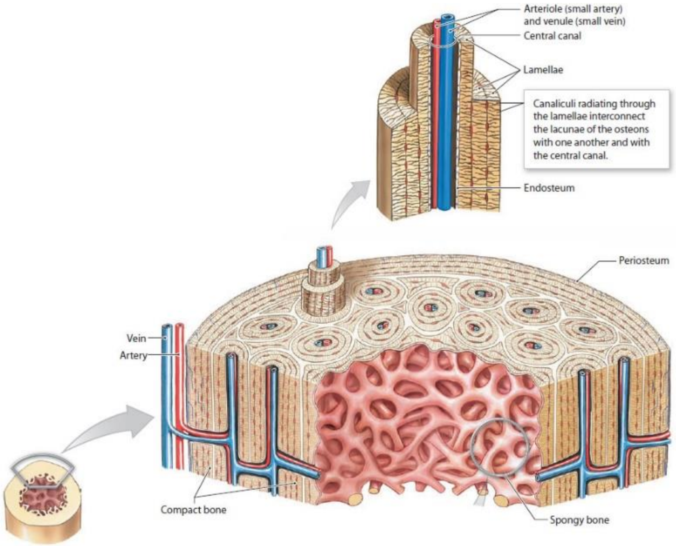


Fig. 3 Section of long bone: a) Compact bone b) Spongy bone [8]

1.2 Surgical drill parameters

Surgical drills just like any other drills has to have such geometrical parameters that could be said are optimal for drilling the bone.

Flute - The standard twist drill geometry is illustrated in Fig. 4 . The body of the drill has two spiral flutes. The angle of the spiral flutes is called the helix angle, a typical value of which is around 30^{o}. While drilling, the flutes act as passageways for extraction of chips from the hole. Although it is desirable for the flute openings to be large to provide maximum clearance for the chips, the body of the drill must be supported over its length. This support is provided by the web, which is the thickness of the drill between the flutes [10]. Flutes for surgical drills have traditionally been helical with U grooves; this is based on the performance of drills against wood which has many structural similarities to bone [11].

Point angle - The point of the twist drill has a conical shape. A typical value for the point angle is 118^{o}. The point can be designed in various ways, but the most common design is a chisel edge, as in Fig. 4. Connected to the chisel edge are two cutting edges (sometimes called lips) that lead into the flutes. The portion of each flute adjacent to the cutting edge acts as the rake face of the tool [10]. The effect of various point and helix angle combinations have been studied. Optimum point angles have been developed by engineers for drills used to machine metals. It is logical to assume that an optimum design exists for stainless-steel drills used against bone. It was showed that a twist drill of 118^{o} point angle and

28° helix angle required much less torque per unit area of hole and energy as well, per unit volume of bone drilled at a given feed rate, compared to a drill with a 60° point angle [11].

Helix angle - Chip removal can be a problem in drilling. The cutting action takes place inside the hole, and the flutes must provide sufficient clearance throughout the length of the drill to allow the chips to be extracted from the hole. As the chip is formed it is forced through the flutes to the work surface. Friction makes matters worse in two ways. In addition to the usual friction in metal cutting between the chip and the rake face of the cutting edge, friction also results from rubbing between the outside diameter of the drill bit and the newly formed hole. This increases the temperature of the drill and work. Delivery of cutting fluid to the drill point to reduce the friction and heat is difficult because the chips are flowing in the opposite direction. Because of chip removal and heat, a twist drill is normally limited to a hole depth of about four times its diameter. Some twist drills are designed with internal holes running their lengths, through which cutting fluid can be pumped to the hole near the drill point, thus delivering the fluid directly to the cutting operation [10]. As the helix angle increases the rake angle also increases and the torque and thrust during drilling decrease. The clearance of bone chips which are short flaky and broken in nature is also assisted by a larger helix angle. The helix angle of a drill bit varies with the drill diameter; larger angles are used for larger diameter drills. The optimum range for the helix angle has been reported as 24–36° [11].

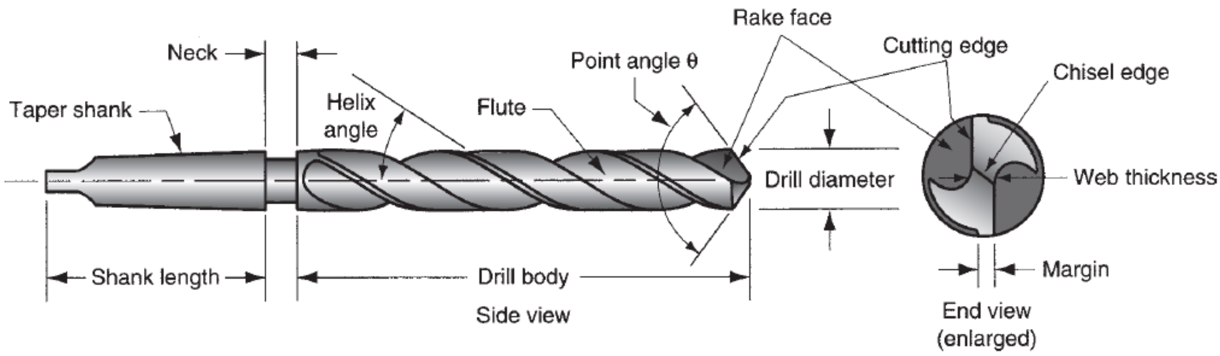


Fig. 4 Standard geometry of two flute twist drill [10]

1.3 Drilling parameters

Orthopedic drilling operations are done by hand, thus optimal operating parameters cannot be guaranteed. Pressure applied by the surgeon with the hand drill onto bone varies significantly and is very dependent on the drill diameter. Some has reported as 10-20N with diameter of 3.2mm [3], while others have found that 110N may indeed be more suitable [1].

It was shown that the temperature increased with an increasing drill speed and decreased with high feed-rates and applied drill forces. The drilling temperatures of the female bovine tibias were found to be higher than that of the male tibias and the drill speed was found to be a significant parameter on the maximum temperature, also the temperature generated when drilling a bovine bone was higher than that produced when drilling human bone [12]. Moreover, the maximum temperature increased with an increasing drill tip angle and bone mineral density [13].

Drills used during preparation of orthopedic operations with self-tapping screws are often used repeatedly until they become blunt and ineffective. Because the sharpness of the drill is one of the most important factors in its cutting efficiency, blunt drills may require the application of extra force, which in turn may contribute to excessive frictional heat produced during preparation of screw holes. Large rises in temperature can impair bony regeneration around screws and contribute to failure of internal fixation. An attempt was made to quantify the effects of blunt drills on the potential increase in temperature, and a significant difference in the temperatures generated by used and new drills was observed. The mean temperature rise for new drill was 7.5 C^o, drill after 600 holes 13.4 C^o and drill from operating theatre 25.4 C^o [14].

Drill geometry also plays a major role in heat production, triple twist drills with a relief angle and double twist drills with a relief angle appear to stay within the accepted temperature parameters, at least up to 25 uses [15].

Feed rate influence on temperature – Increasing feed rate increases the temperature, but it is offset by shortened time of operation, thus giving positive net result. Keeping in mind that these operations are done by hand, feed rate as a parameter should be disregarded, an applied force should be used instead.

Low speed drilling – speed below 3000 rpm is said to be low speed drilling, many articles indicate the optimal drilling speed somewhere in between 800 and 1400 rpm [12], [16], [1].Though it is known that speed depends on force, it was found that there were differences as high as 50% between the free-running speed and the speed under load. Therefore, definitive conclusions about temperature dependence on speed would be much more meaningful if temperature rise were correlated with actual drill speed [17].

High speed drilling - Experimental high speed drilling results show that the temperature rise and the duration of temperature elevation decreased with speed and force. Heat generation and heat transfer to bone are dependent on two factors: the rate of heat generation - which is expected to increase with speed and force - and the duration of the drilling or cutting process - which decreases with speed and force. With drilling at high speed and increased force, the temperature rise is small because the increased speed of penetration of bone leads to an overall decrease in drilling time. This indicates that at high speed and great force the drilling time is the dominant factor in determining the amount of heat generation and heat transfer to bone [17].

1.4 Vibration assisted drilling

The working process of a vibration assisted machine is performed by subjecting its tool to a combination of two motions. A driving motion program is required to shape the work piece. A vibration of specific direction, frequency and intensity is then superimposed. The construction of the machine and its elements depends critically on the process being performed by the tool. A transducer generates vibration which is then transmitted to the tool via a vibration system, often with a change of direction and amplitude [18]. Currently there two major branches of vibration assisted machining, that is ultrasonically assisted machining and low frequency assisted machining (or simply vibration assisted machining).

1.4.1 High frequency assisted drilling

High frequency assisted drilling or ultrasonically assisted drilling is a hybrid machining technique, which has been used to machine conventional metals and new exotic materials and advanced composites. In UAD high-frequency (> 20 kHz) vibration is superimposed on a standard twist drill bit, preferably, in the axial direction. This vibration is generated by piezoelectric transducers and applied to enhance the cutting process. There are several advantages of UAD over CD such as the reduction in thrust forces and torque, better surface finish, low tool wear and elimination/reduction in burr formation. As drilling-thrust forces have a direct effect on machining-induced damage, there has been several studies performed over the last few years which indicate that vibrating the drill bit in the axial direction yields the maximum reduction in drilling-induced damage [19].

1.4.2 Low frequency assisted drilling

Vibration-assisted drilling (VAD), unlike UAD aids the cutting motion of the tool by adding small-amplitude, low-frequency tool displacement to the tool during cutting [7]. For appropriate combinations of cutting velocity, tool amplitude and frequency, the tool periodically loses contact with the chip. As a consequence, machining forces can be reduced and thinner chips can be generated. This leads to improved surface finishes, better form accuracy, and near-zero burr compared to conventional machining [20]. Tool life, especially of diamond tools for cutting ferrous materials, is dramatically extended by VAD. When cutting brittle materials, VAD has also been found to increase the depth of cut for which ductile-regime cutting can be achieved, allowing complex optical shapes to be made without grinding and polishing [19].

2. ANALYSIS OF LOW FREQUENCY VIBRATION ASSISTED DRILLING

Relevance and problem of the research

Vibration assisted machining exerts lower forces onto the machined piece, produces better surface finish. An experiment by Alama, Mitrofanova and Silberschmidta was conducted to determine the forces exerted on the bone in CD and VAD. The results show that forces obtained in the given conditions are lower when using VAD [2]. Thereby one can assume that the temperatures on the bone-drill interface should as well be lower. A common problem with contemporary bone fixation methods is the drilling of the hole, as the result completely depends on the skill of the surgeon, also as was mentioned earlier, if the bone is heated above 50^{o} C, the bone tissues are damaged irreversibly. There have been numerous propositions with varying degrees of success on how to combat the excessive heat [1], [12], [15], [16], [18]. Mainly it was done by changing geometrical parameters of the drill bit, applying internal or external irrigation systems, using robotic systems. Knowing all that, two experiments are proposed to find the temperature difference between conventional drilling and low frequency vibration assisted drilling.

Aim of the first experiment is to get results that are in line (if possible) with the scientific community, while keeping the experiment simple. The following are the objectives of the experiment:

Design and conduct experiment;

Analyze obtained data;

Observe drawbacks;

Propose possible solutions.

Aim of the second experiment is to compose and conduct an experiment both with PMMA and bovine bone, taking into account previous experimental results. The following are the objectives of the experiment:

Review previous experiment;

Design and conduct improved experiment using PMMA;

Analyze obtained data and select most promising vibration modes;

Repeat experiment using bone samples;

Analyze obtained data;

Observe drawbacks;

Propose possible solutions.

2.1 Low frequency vibration assisted drilling experiment 1

In conventional vibration assisted drilling systems, the tool gets excited axially, parallel to feed rate, the work piece remains stationary and then the interaction occurs. In order to design and test the experiment it is deemed important to make it as simple as possible, as to reduce the uncertainty of various factors. The decision is made to oscillate the sample instead of the tool (**Fig. 5**), and instead of VAD system to use a simple hand drill. In essence the interaction of tool with sample is completely the same, material is being removed while the drill bit oscillates parallel to applied axial force.

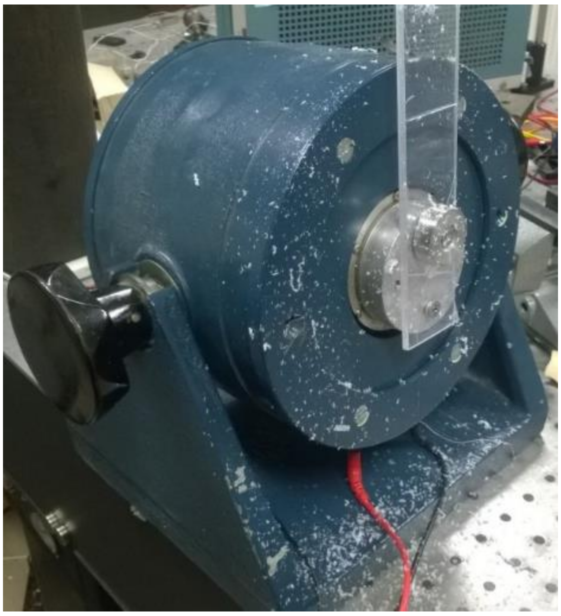


Fig. 5 Electromagnetic vibrator with attached sample

Measuring temperature at drill – sample interface is a challenge, even if thermal properties of the material are fully known, and it is said to be homogenous (as is the case with PMMA sheet), thermo couples are inert, thus making it hard to measure instantaneous temperatures at contact. Solution that is proposed is to measure temperature at the moment the drill exits the exit hole (**Fig. 9**). For this a thermal camera is used, the whole drilling process is filmed, when the exit hole appears, the maximum temperature (T_{max}), and drilling times are obtained.

2.1.1 Samples

According to several sources [29], [4], PMMA (Poly - methyl methacrylate) is a suitable substitute to a bone in an experimental setup. This material is homogeneous and it removes natural variation that could appear between bone samples, thus making it a perfect candidate to test the experiment. Because it is easy to shape no special rigs were needed to mount it to electromagnetic vibrator.

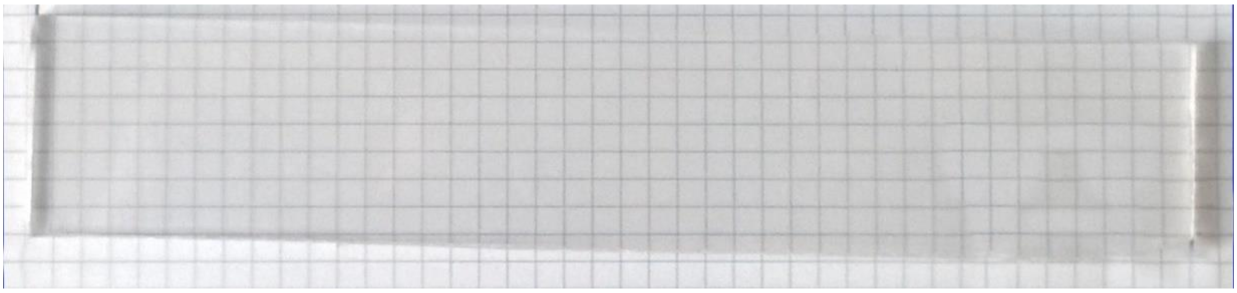


Fig. 6 PMMA sample

The samples are 4mm thick and cut to 200mm by 40mm slabs (**Fig. 6**). Vibrating the samples in a range of frequencies it is possible to observe the start of the resonant frequency range where amplitude of vibration starts to rise drastically. It is experimentally observed that the sample starts resonating at 60Hz, thus it is deemed appropriate to oscillate samples every 10Hz until resonant frequency (10Hz-50Hz).

2.1.2 Drill selection and drilling parameters

According to literature drill material has little to no effect on the bone cutting temperature [21], carbide drill-bits should be used to reduce the effect of drill bit wear [22]. 2.5 mm to 3.5 mm diameter drill-bits with 118^{o} point angle, 20^{o} helix angle, and straight cutting edges are known to produce satisfactory results [23], [3]. While lower diameter drill bits show satisfactory results, these results are satisfactory if the drill bits are sharp, this as has literature shown, is not always a fact [7]. For experimental purposes, a two flute drill bit [24], with a diameter of 4.2mm, which is known to produce higher temperatures than appropriate is used, to better show the benefits or drawbacks of vibration assisted drilling.

During drilling procedures surgeons apply varying amount of force, which depends on particular surgeon, drill bit wear, type of drill used. Considering reviewed articles [1], [26], it is judged appropriate to apply pressure by hand, in combination with 1200 rpm drill cutting speed. For the sake of the experiment a HSS DIN 338 twist drill is selected (**Fig. 7**). All in all ten such drills are then used in both experiments so that not one of them would have more than 25 drilling operations done and each could be said was reasonably sharp [8], [7].

Fig. 7 Twist drill HSS DIN 338

2.1.3 Equipment

Equipment was obtained from and experiment was conducted at the Institute of Mechatronics with the supervision of Dr. Vytautas Jurėnas. **Table 2** shows Equipment utilized in experiment 1 as well as in experiment 2. It should be noted that experiment 2 utilized all the equipment in the table, whereas experiment 1 only a subset of equipment. Detailed technical data for the used equipment can be found in Annex 1.

Table 2 Equipment

<table>
<tr><td rowspan="11">Experiment 2</td><td rowspan="6">Experiment 1</td><td>Signal Generator</td><td>WW5064</td></tr>
<tr><td>Amplifier</td><td>VPA2100MN</td></tr>
<tr><td>Electromagnetic vibrator</td><td>VEB ROBOTRON MESS-ELEKTRONIK OTTO SHON</td></tr>
<tr><td>Drill</td><td>Makita 8391DWPE</td></tr>
<tr><td>Drill bit</td><td>HSS DIN 338 twist drill</td></tr>
<tr><td>Thermal camera</td><td>FLIR T450sc</td></tr>
<tr><td></td><td>Accelerometer</td><td>Schwingungsaufnehmer KD35 Accelerometer</td></tr>
<tr><td></td><td>Oscilloscope</td><td>PicoScope 4226</td></tr>
<tr><td></td><td>Force sensor/indicator</td><td>FORCE / TORQUE gauge MODEL BGI – Mark-10</td></tr>
<tr><td></td><td>Rail</td><td>DIN TH3.5 15 Rail</td></tr>
<tr><td></td><td>Holder</td><td>DIN TH3.5 7.5</td></tr>
</table>

Block diagram below (**Fig. 8**), indicates how the equipment is set up, and relationships between them. Signal generator generates sine wave of a particular frequency, amplifier then amplifies it to a certain degree to drive the electromagnetic vibrator. Drill is then used on the sample, while it is being filmed by the 20hermos-graphic camera.

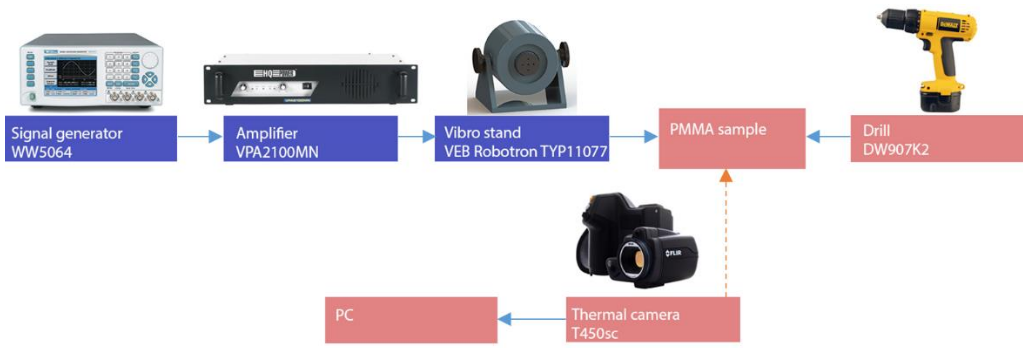


Fig. 8 Block diagram for the first experiment

2.1.4 Course of experiment

Conventionally vibration assisted machining is done by superimposing auxiliary oscillating movement to the tool, which as mentioned before helps along with the material removal processes. To simulate such an arrangement in a cheaper and simpler fashion, the sample is oscillated in a range of frequencies (from 0Hz to 50Hz every 10Hz), oscillation direction is parallel to feed direction of the drill. Thermal camera is pointed to the expected part of the exit hole as shown in **Fig. 9** and the whole endeavor is filmed. Later obtained films are analyzed using FLIR Tools software.

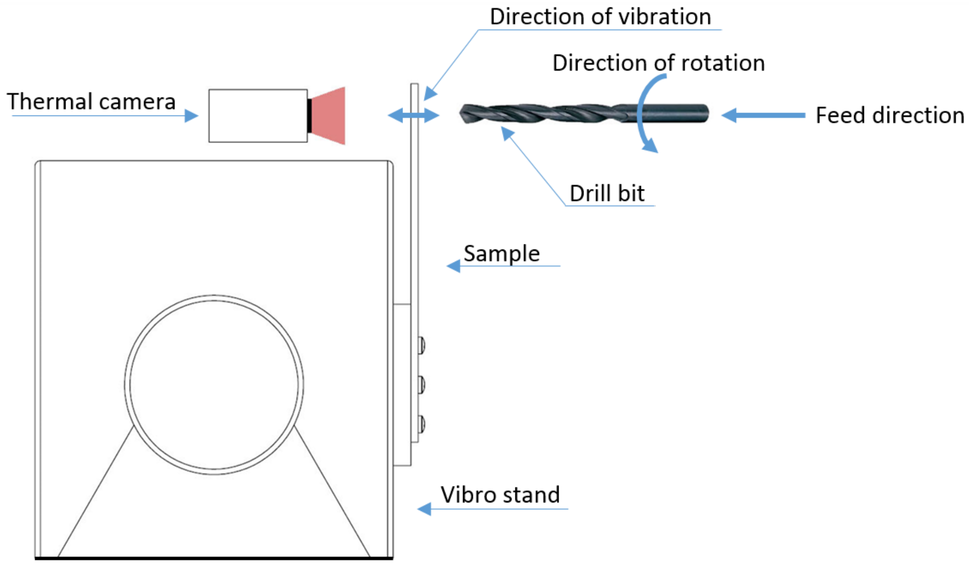


Fig. 9 Scheme for the first vibration-assisted drilling experiment

The following are the basic steps for the experiment:

- Sample preparation – samples are cut to size, necessary holes are drilled;
- Assembly - sample is attached to electromagnetic vibrator (**Fig. 5**);
- Oscillation selection – appropriate frequency is selected for the signal generator, signal amplification level (amplitude) is selected for the amplifier;
- Camera setup – thermal camera is put behind the sample, it is directed at the center of the drilling point;
- Result gathering – drilling is started at the same time as filming to obtain not only thermal data, but also to get the drilling time;
- Result review – results are analyzed, possible drawbacks and strengths are observed, ideas for future consideration proposed.

Drilling the first few samples, a rather big sample deflection was observed, at first it was thought of as a hindrance with possible negative effects on the experiment (though it may still be). But utilizing the flexibility of the sample and maintaining the same angle of deflection it was easier apply the same axial pressure on the sample. It made, at least in authors opinion, hand drilling between samples more consistent, otherwise more drastic and uneven results may have been obtained.

Table 3 Main experimental conditions for experiment number 1

Drill bit	Material Diameter Point angle	HSS 4.2 mm 120^o
Number of revolutions		1200 rpm
Low-frequency vibration	Frequency range	0Hz-50Hz
Work piece	Material Thickness	PMMA 4 mm
Temperature	Ambient	18 C^o

2.2 Low frequency vibration assisted drilling experiment 2

Experiment 2 uses the same basic premise as experiment 1. Samples are vibrated in a particular frequency and amplitude, at the same time they are drilled and filmed with 22hermos-graphic camera. 10 holes are made in each vibration mode when drilling PMMA. When drilling bone, each sample is drilled with all the selected vibration modes. This is done in order to see the effect different vibration modes have on the same bone. Experiment was done in two phases, during first phase a set of frequencies and amplitudes was selected for PMMA sample drilling. Obtained results were analyzed and vibration modes which showed the greatest effect were chosen for the second experimental phase, where bovine bone samples were drilled.

To reduce uncertainty from previous experiment a new setup is proposed, **Fig. 10** illustrates the difference. Rail is connected to the table as a cantilever, and electromagnetic vibrator is attached to the said rail. Force and acceleration sensors together with sample are attached to the free end of the rail. This solves several drawbacks of the previous experiment, such as lack of rigidity, uncertainty of applied force. Samples are put into a special bracket (to give them more rigidity) and drilled by hand while observing the force sensor indicator.

The resonant frequency of this system is 40Hz, it was decided to use frequencies above the natural frequency. For this reason it was not possible to reproduce results from previous experiment with this improved setup as the frequency range used in experiment 1 was 0Hz to 50Hz.

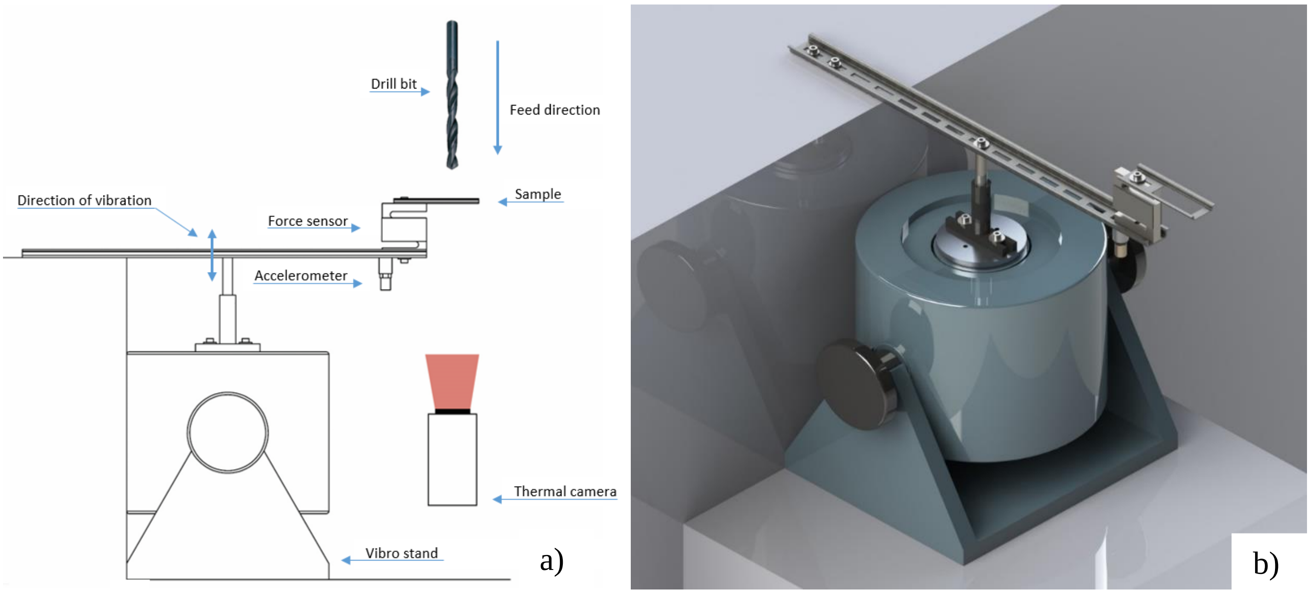


Fig. 10 Design of the experiment a) Scheme b) Render of experimental setup

2.2.1 Samples

Like in the first experiment PMMA is used to test the setup, and to select most suitable vibration modes. The samples were 4mm thick and cut to 100mm by 20mm slabs (**Fig. 11** a)), compared to 200mm by 40mm from previous experiment. Samples were smaller in order to reduce possible deflections, and to fit the holder which gave them more rigidity.

Bone selection was determined by the shape of bone, not its physiological function. In order to easily use the same setup instead of long bones (femur, tibia), bovine ribs were used **Fig. 11** b). The thickness of the compact bone was taken into account, and could not be less than 4 mm. Several different bones were used, each of them were cut to 100 mm length and their thickness at the center were noted in **Table 4**.

Table 4 Main parameters of bone samples

	Bone 1	Bone 2	Bone 3	Bone 4	Bone 5
Whole bone thickness, mm	17	20	25	22	18
Compact bone thickness, mm	8	9	10	9	9
Bone length, mm	100	100	100	100	100

Bovine bone samples were obtained from local butchers, these specimens were not frozen (in order to not to disturb internal structure), but instead refrigerated according to hygiene requirements. Individual samples were cut from different ribs using a hacksaw. The samples that were used had to fit the holder and stay fixed when bound with cable ties, for this reason only relatively flat and straight bones had to be used. The parameters from **Table 4** should be taken as cursory, the bone thickness along bone varies, as well as the amount of compact bone. The thickness of the whole bone was measured at the center with caliper, the amount of compact bone was measured at the end of the bone where different types of bone were plainly visible. In hindsight after drilling the bone with different vibration modes it would have been better to cut the bone across the drill holes, and to measure particular thickness at every drill hole of each cut.

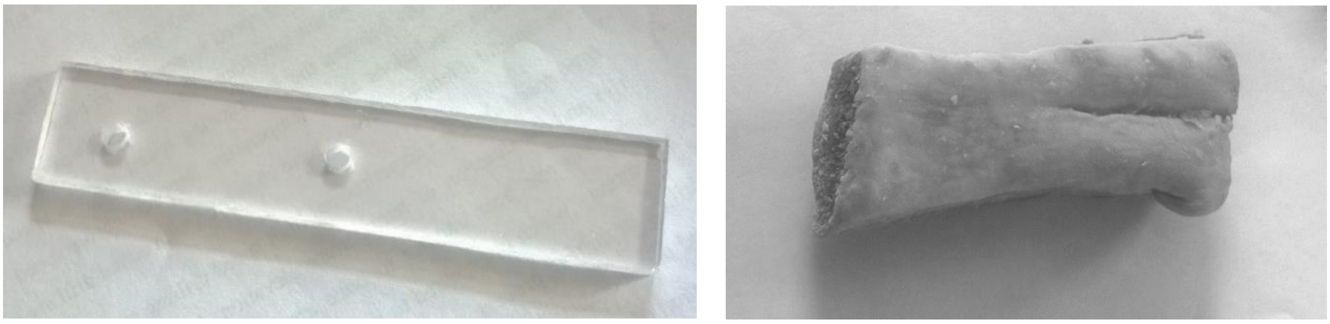


Fig. 11 Samples a) PMMA b) Bone

Sample holder was made out of DIN mounting rail TH35-7.5 (main rail was TH35-15), as can be seen in **Fig. 12**. Main functions of this sample holder ware to easily accommodate both PMMA and bone samples, as well as to suppress the excessive bending of the samples while maintaining exit hole visible. This implement was cut to 110 mm in length, the hole was made using angular grinder. Samples were attached with cable ties for easy and fast assembly and disassembly. In the future stainless steel cable ties could be used.

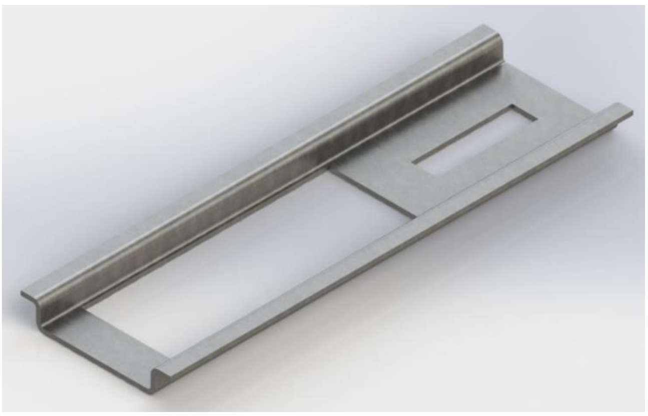


Fig. 12 Sample holder

2.2.2 Design and course of the experiment

Previous experiment (experiment number 1), showed areas that needed improvement in the setup and possible solutions were discussed. While designing the second experiment it was deemed important to detect force with which drill was pressed on to the sample. For this reason force sensor MARK-10 was utilized. Another important area that needed rethinking was rigidity of the sample, as a possible solution a U-shaped aluminum sample holder was proposed (**Fig. 20**). During early stages of design the idea was scrapped for a more practical rail design which could more easily accommodate sensors, as well as provide a more conventional drilling experience (horizontal versus vertical, **Fig. 10**). Unlike in the first experiment where samples were of the same size, this experiment utilized same sized PMMA and irregularly shaped bone samples, so setting specific amplitude setting on the amplifier would not give consistent results. A need to obtain a comparable amplitude between different sized samples was observed, for this purpose an accelerometer was used. Note, actual amplitude (magnitude), is not important.

While trying the experiment instead of thermo-graphical camera a non-contact IR thermometer was tested (**Fig. 13** a)), as it had one obvious pro – it could log temperature history. After testing, a major con was observed – the thermometer was very inert as it could only measure temperature every second. Because the drilling process was comparatively fast (4-8 seconds), only few points of data could be observed and they were wildly inconsistent between each other. In comparison thermo-graphic camera FLIR T450sc has four times better resolution, it measures temperature every ¼ of the second.

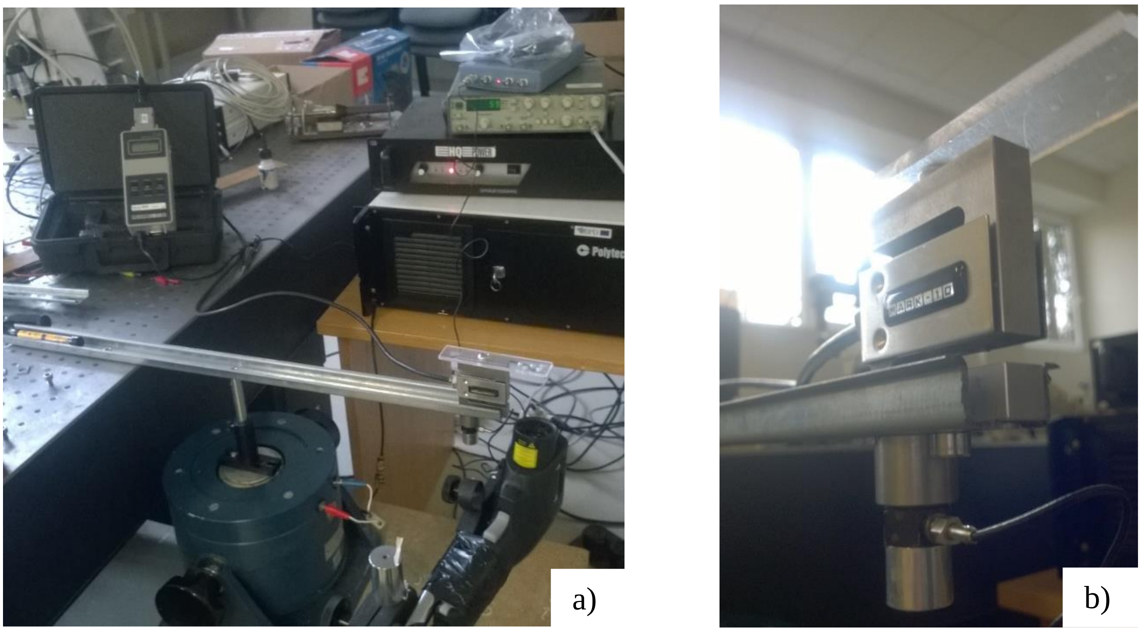


Fig. 13 a) Experimental setup with non-contact infrared thermometer b) Closer view of sample-sensor configuration

When this experiment was in early planning stages, a decision was made to drill at least 10 holes using a single vibration mode (frequency + amplitude), as well as to use about 30N of force while drilling, thus main experimental conditions for the second experiment (**Table 5**) were laid out as a blueprint to adhere to.

Resonant frequency of the second experiment was found to be lower than that of the first one. Frequencies above natural frequency of the system had to be used (60Hz and more), or else a very small frequency range would have been utilized. Decision was made to forgo experimenting at 0Hz to 30Hz and instead to try using frequencies in the range of 60Hz to 120Hz.

Table 5 Main experimental conditions for experiment number 2

Drill bit	Material	HSS
	Diameter	4.2 mm
	Point angle	120
Number of revolutions		1200 rpm
Applied force		~30N
Low-frequency vibration	Frequency	60Hz - 120Hz
Work piece	Material	PMMA
	Thickness	4 mm
Work piece	Material	Bone
	Thickness	17 mm- 26 mm
Temperature	Ambient	19 C^{o}

Selecting vibration modes was done during the experiment testing phase, frequencies and amplitudes were chosen which seemed to show the strongest effect. Selected modes and the obtained data can be seen in **Fig. 21**. After doing the first part of the second experiment (drilling PMMA), modes that show the biggest positive effect were chosen for the bone drilling experiment.

Block diagram below (**Fig. 14**), shows the basic relationship between utilized equipment. Signal generator creates a sine wave of particular frequency and amplitude, amplifier amplifies the amplitude of the signal and sends it to electromagnetic vibrator. To maintain repeatable amplitude between drilling sessions' accelerometer is utilized, it is connected to an oscilloscope which indicates the signal. In order to get as repeatable results as possible a force sensor which is connected to its indicator is also used. The location of the exit hole of the sample is filmed by thermal camera while it is being drilled.

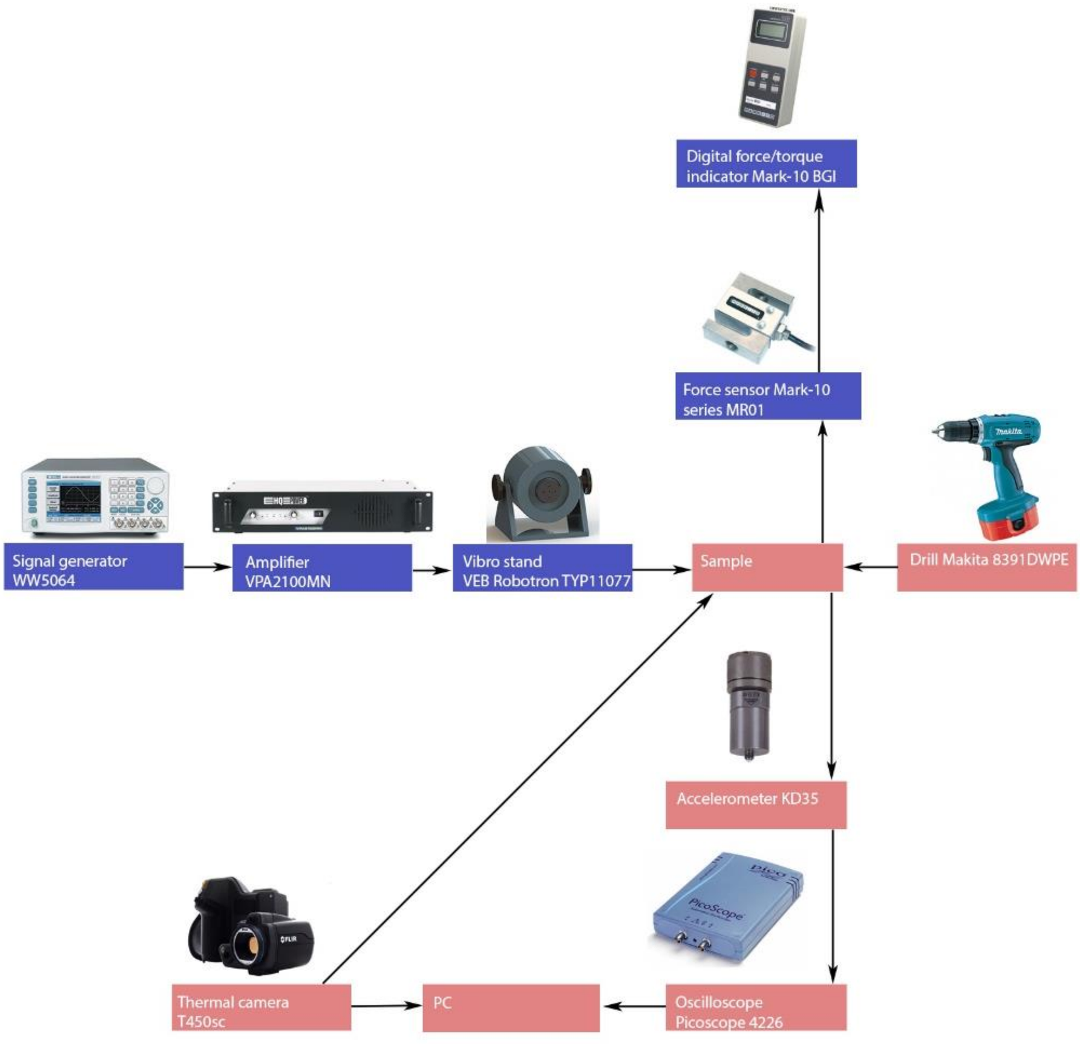


Fig. 14 Block diagram of experiment 2

The following is the algorithm of the experiment:

- Sample preparation – PMMA sample is cut to size, necessary holes are drilled, for bone drilling experiment - bone is cut to length, positioned on the sample holder and tied with cable ties;
- Assembly – assembly of the experimental setup. Rail is connected to the table as a cantilever, it is also the connected to the electromagnetic vibrator. Force and acceleration sensors are connected to the rail. Sample holder is connected to the force sensor.
- Oscillation selection – appropriate frequency is selected for the signal generator. Signal amplification level (amplitude), is determined by the accelerometer data and selected on the amplifier;
- Camera setup – thermal camera is put below the sample, at an angle (**Fig. 15**).
- Result gathering – drilling is started 10 seconds later than the filming begins to obtain not only thermal data, but also to get the amount of time it takes to drill the hole. While drilling, the applied force on the sample is observed constantly;

- Result review – results are analyzed.

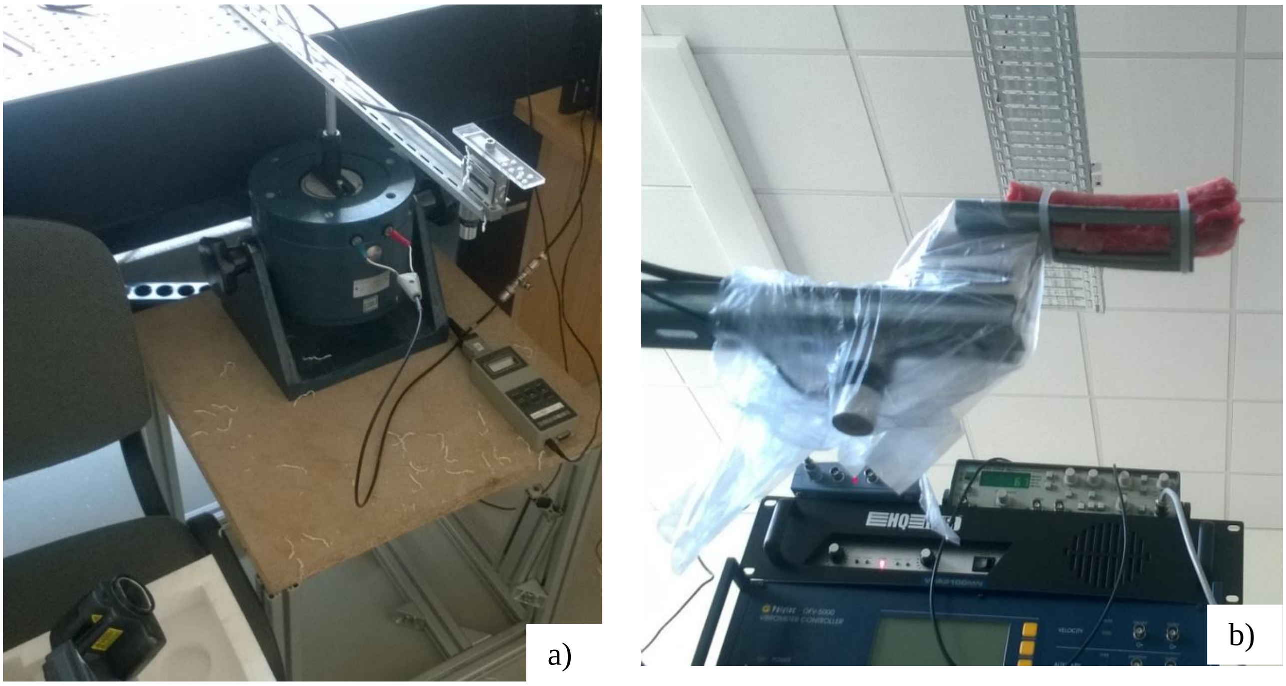


Fig. 15 a) Experimental setup using thermal camera FLIR b) Thermal camera point of view

Camera positioning: During the first experiment thermographic camera was positioned in front of the exit-hole (**Fig. 9**), the sample was parallel to camera lens. The experiment was vertical in its nature, the chips could not hit the camera lens, that particular setup worked. The second experiment was horizontal in its nature, to replicate first experimental setup, the camera should have been positioned below the sample, where falling chips would have led to possible lens contamination or even damage. To eliminate this problem in the second experimental setup a decision was made to move the camera away from the sample and point it at an angle, so it would still be possible to obtain thermographic images at the instant the drill penetrates the sample. The camera was positioned 1 meter away (as per user manual), from the sample so it could have the best focus of the sample. As can be seen in **Fig. 15** b) which shows the point of view of the camera, the location where the exit hole is supposed to appear is completely visible.

Samples were positioned on the sample holder and held in place with simple plastic cable ties. The cable ties might not be the most robust connector available, but for fast sample fixation and removal it did its job perfectly.

PMMA drilling: Each PMMA sample was drilled 5 times, holes were made in succession just like shown in **Fig. 16**, first hole was closest to force sensor, fifth was farthest. That means two samples were needed to be drilled to obtain average for that particular vibration mode. One could argue that forces acting on the sensor should be higher while drilling farther away from the force sensor, and that would be completely correct, but because in each vibration mode samples were drilled 5 times, and because only their averages were taken, the effect different drilling positions have on the experiment is negligible.

Bone drilling: Unlike drilling PMMA which is a homogenous material, and every sample has the same properties, each bone sample is distinct, for this reason every bone sample had to be drilled applying every mode of vibration. That means Bone 1 had to be drilled applying 0Hz 0mV, 60Hz 80mV, 100Hz 80mV, and 120Hz 100mV auxiliary motion, the same with Bone 2, and so on. In order for the experiment to be as unbiased as possible, every mode of vibration was given a number from 1 to 4, each number then was given a drilling position on a particular bone, as illustrated by **Fig. 16**. This way the effect of drilling position is minimized, every mode of drilling should have had the same average force applied.

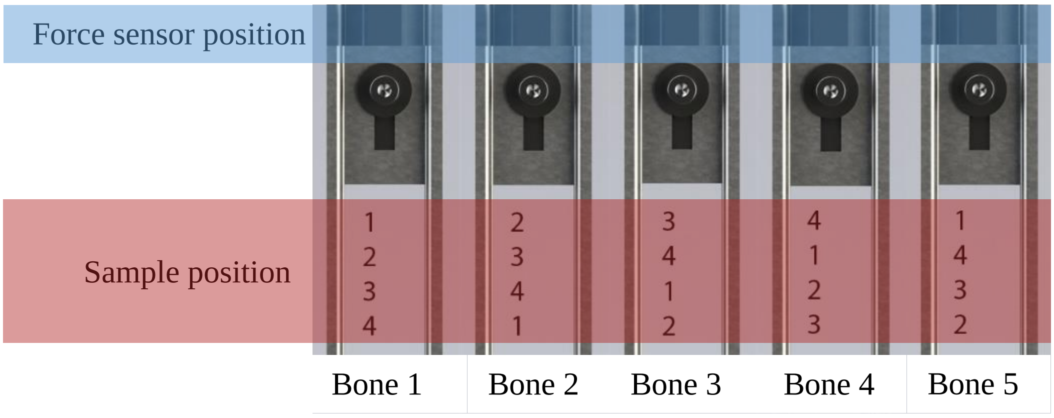


Fig. 16 Top view of sample holder, drilling mode and postion overview

Drilling observations: positioning and the beginning of the drilling process was more difficult in some vibration modes than in others. Some samples at particular vibration modes would move at a rather big amplitude and the drill would jump of the specimen and could not remove any material, making it impossible to drill in the assigned drilling position. For this reason some samples had dimples made with an awl, which then easily guided the drill tip into the needed position. Though both materials PMMA and bone are brittle, because PMMA is homogenous it produced longer chips compared to bovine bone.

Bone drilling was an absolutely different experience compared to PMMA drilling, first of all the difference in thickness was apparent which made the drilling process seem long, applied force seem low. Secondly when drilling bone it did not produce long chips, the biological material was ground up and removed by the flutes of the drill. Thirdly it was obvious that the drill bits used in this experiment were just long enough for the utilized bones, if in the future a similar experiment would be made, but instead of rib bones long bones would be used, longer drill bits should be used. Conversely to PMMA drilling, while drilling bone using selected vibration modes, the positioning of the drill on the sample was rather easy, it might be due to the fact that the modes that were selected were the modes that stood out in easy positioning, or it could have been due to inherent bone brittleness which helped to position drill tip.

3. EXPERIMENTAL DATA AND DISCUSSION

In this research thermo-graphic images of samples are analyzed. It is believed that the maximum temperatures obtained in every sample is at the instance the drill completely penetrates the material and exits through the exit hole. Data obtained from both experiments is discussed in this chapter.

3.1 Data regarding experiment number 1

Images ware extracted from thermo-graphic films that ware taken by T450sc. Before drilling, the temperature of samples is measured and noted to be 18°C. Samples are then drilled with selected vibration modes. Data is then used to chart several different graphs.

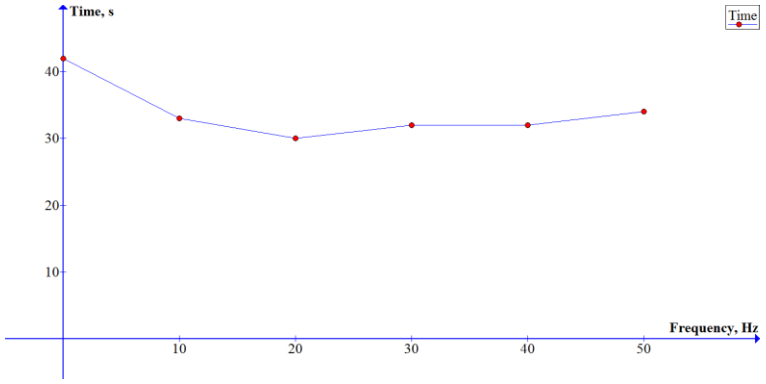


Fig. 17 Drilling time dependence on the frequency of sample vibration

Sample which had no oscillations applied had the longest cutting time of 42 seconds, the fastest one was when vibrations of 20Hz were applied, at 30 seconds. Interestingly an increase in cutting time may be observed by increasing frequency, but this may be due to inability to apply steady axial force to the sample when drilling.

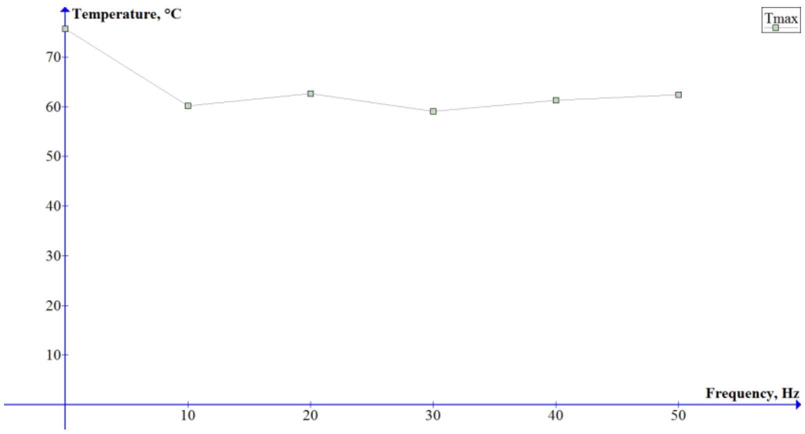


Fig. 18 Temperature dependence on the frequency of sample vibration

First sample (0Hz) had the highest exit temperature at 75.6°C, while the lowest was observed on sample 4 (30Hz) at 60.1. Detailed data of the first experiment with thermo-graphic images can be found in ANNEX 2.

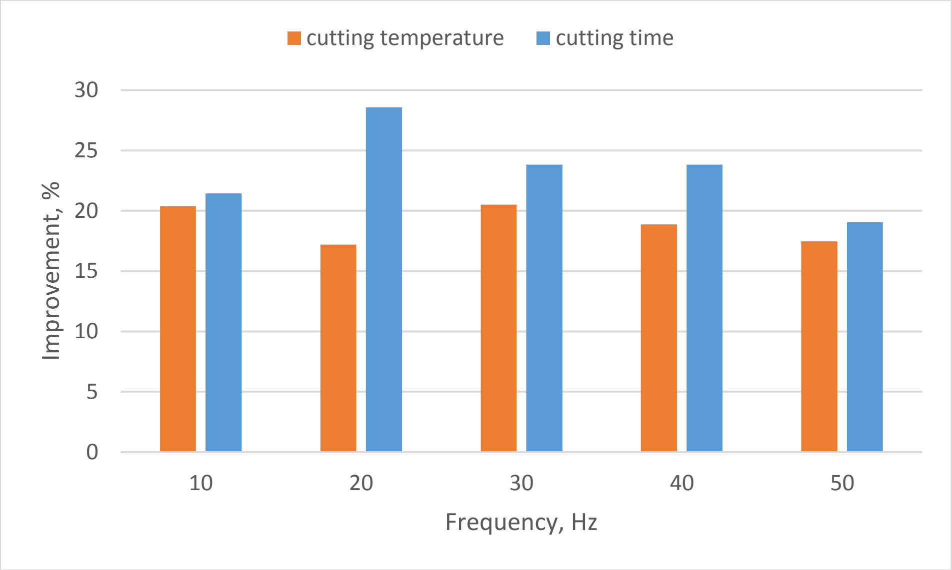


Fig. 19 Improvement of cutting parameters in the given frequency range

Calculating improvements, in this case reduction in cutting time and obtained maximum temperature ((T0-Tx)/T0*100%), where T0 is the obtained maximum temperature of sample that was not vibrated, Tx is the obtained temperature of sample that was vibrated at x Hz). As can be seen in Fig. 19 the greatest improvement in cutting temperature as a drilling parameter (greatest reduction in cutting temperature) is at 30Hz frequency, whereas greatest improvement in cutting time is at 20Hz. A trend can be seen that the cutting temperature improvement is a bit lower than the cutting time improvement, that means, and data from 20Hz shows it the best, that lowering cutting time does not necessarily mean greater improvement in cutting temperature. All cuts were done by hand, and as such the third sample (20Hz), may have been cut using more force, it may be why such stark contrast of cutting temperature and cutting time may be observed compared to other samples. This experiment was designed to test thermal properties, as such best drilling parameters are obtained oscillating sample at 30Hz.

3.2 Discussion regarding experiment number 1

Using the described experimental setup it was observed that applying vibration to the sample reduces cutting temperature and cutting time. Sample 3 which was oscillated at 20Hz showed decrease in cutting time by 27% compared to the Sample 1 (0Hz), Sample 2 and Sample 4 showed 20% decrease in cutting temperature compared to Sample 1.

The proposed temperature measuring method (thermo-graphic imaging of exit-hole), proved to be simple, precise and easy solution to a problem which becomes that much harder when a nonhomogeneous material is drilled.

In order to further improve research in this topic, main drawbacks are shown and possible solutions are proposed:

Problems:

Uncertainty on force applied – the biggest problem with the conducted experiment was the uncertainty of the force applied while drilling the sample. The variation of force may have led to the obtained results.

Deflection of the sample – PMMA sample was 4mm thick, and taking into account its length (200mm) rather flexible.

Poor exit-hole finish – the deflection of the sample led to rather poor hole-finish.

Solutions:

Force sensor – To remove the variation of force applied while drilling the sample, a force sensor between sample and electromagnetic vibrator may be used to determine the pressure applied.

Increased rigidity - U shaped aluminum sample holder bay be used to increase the rigidity of the system (**Fig. 20**).

For future consideration:

Repeat PMMA drilling experiment using proposed improvements;

Conduct bone drilling experiment.

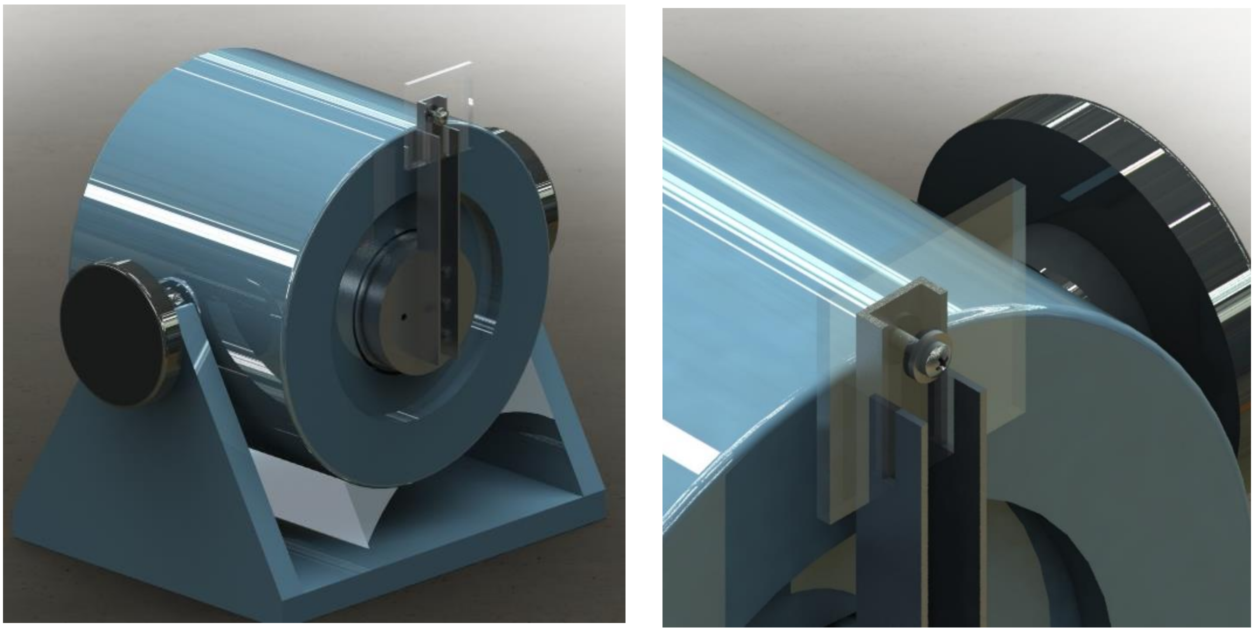
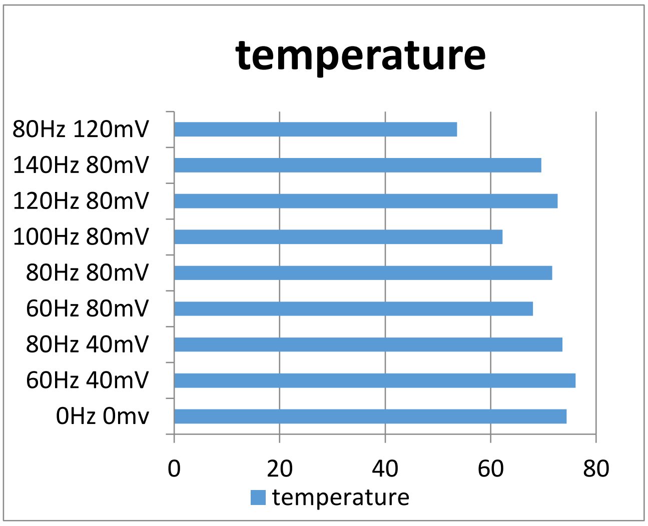


Fig. 20 Experiment 1 proposed sample holder

3.3 Data regarding experiment number 2

Images ware extracted from thermo-graphic films that ware taken by T450sc. Before drilling, the temperature of samples was measured and noted to be 19°C. PMMA samples were then drilled with selected vibration modes at least 10 times. Averages of obtained data is then used to chart several different graphs. Each sample is drilled by hand applying approximately 30N of force.



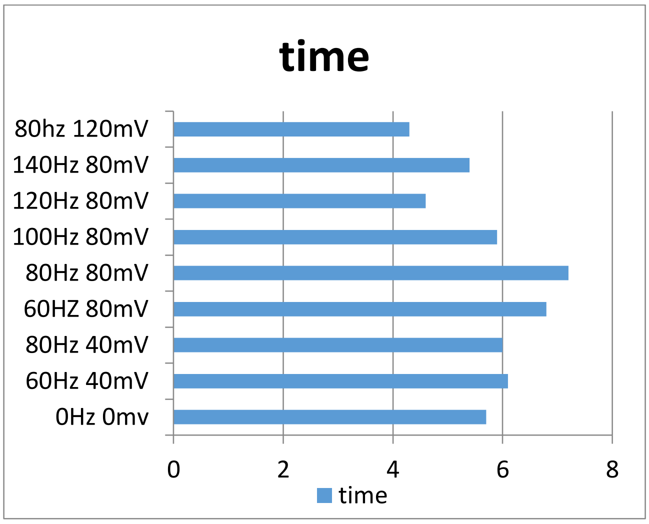


Fig. 21 PMMA drilling a) Temperature dependency on vibration mode b) Time dependency on vibration mode

First batch of data in the second experiment came from PMMA drilling. As seen in **Fig. 21** a) it is obvious that some modes of vibration assistance has little to no effect on the obtained temperature at the exit hole. Modes that show the least positive effect on the drilling temperature are 60Hz 40mV and 80Hz 40mv (these modes show increase in drilling time as well), in essence one could argue that the amplitude at which these samples were oscillated was not suited to produce positive results. Samples which had their amplitude signal set at 80mV, more or less showed positive results. In particular, samples with frequency of 60Hz and 100Hz show sizeable decrease in temperature of 6°C degrees and 11°C degrees respectively. Vibration mode of 80Hz 120mV showed the greatest promise, as it not only drastically decreased drilling temperature by 21°C, but also had a 1.4 second faster drilling time. The apparent randomness of which modes have what effect might be attributed to the uncertainty at what speed the hand drill drilled the material at.

Investigating **Fig. 21** b), it is apparent that auxiliary vibrations in some modes have a negative effect on drilling time, this may be due to the harder positioning of the drill onto the sample when it oscillates, higher frequencies stabilizes the sample and positive effect is observed. As the drilling process of PMMA is relatively fast, measuring errors coupled with a relatively small difference between drilling times could have led to obtained results.

Vibration modes that show biggest reduction of temperature (80Hz 120mV, 100Hz 80mV and 60Hz 80mV), are then selected for the following bone drilling experiment. Detailed data of PMMA drilling can be found in Annex 3.

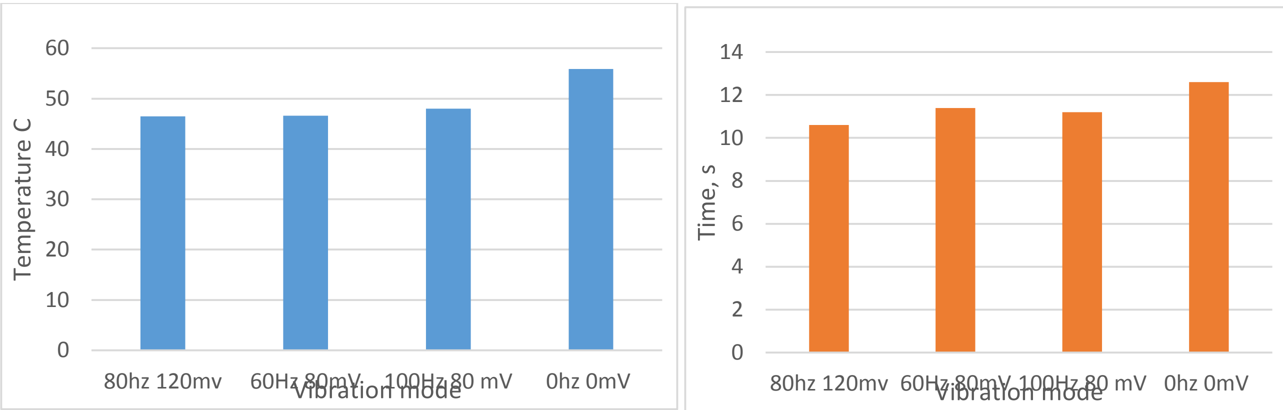


Fig. 22 Bone drilling a) Temperature dependency on vibration mode b) Time dependency on vibration mode

For the second part of the experiment five rib bones were cut to an appropriate size as was discussed in **Table 4** . Selected bones had to have at least 4mm of compact bone, each sample was then drilled with every vibration mode and compared. Every bone is drilled with all the selected modes of vibration. That means Bone A was drilled at 80Hz, 120Hz and so on. It is necessary to do so, because bones have wildly different properties one from the other. It is said that two bones from the same individual can have as much difference in amount of compact bone material as it would be difficult differentiate individual from another based solely on amount of compact bone [9]. **Fig. 22** shows how each vibration mode compares. Average temperature of samples with no vibration applied reveal higher average temperatures than the vibration assisted samples. Specimens which were not vibrated have had average temperature of 55°C, while oscillated samples were near 48-46°C temperature, which is at the limits of safe temperature range.

Table 6 Obtained bone drilling data

	Mode 1			Mode 2			Mode 3			Mode 4		
	80hz 120mv	temp	time	60Hz 80mV	temp	time	100Hz 80 mV	temp	time	0hz 0mV	temp	time
Bone 1	384	45.1	10	386	46.6	12	385	47.1	9	383	49.3	10
Bone 2	389	50.6	11	388	52.7	13	390	51.3	12	387	59.8	14
Bone 3	394	52.9	13	395	51	12	393	53	13	391	66.9	16
Bone 4	398	39.1	9	397	39.9	10	399	42.8	11	396	56.7	12
Bone 5	402	44.6	10	403	42.7	10	401	45.9	11	400	46.8	11
avarage		46.5	10.6		46.6	11.4		48	11.2		55.9	12.6

Investigating in detail the data in **Table 6** it is apparent that low frequency vibration assisted drilling had positive effect on the drilling temperature. Positive in this sense that all the temperatures that were obtained, were lower than the temperatures obtained with common drilling. Utilizing vibration assisted drilling it was possible to obtain temperatures of less than 50°C in three samples out of five in every vibration mode, where in common drilling in two out of five. The lowest drilling temperature of 39.1°C was achieved drilling Bone 4 and applying Mode 1 vibrations, this might be due to lower compact bone content and the overall thickness of the said bone. In general Bone 4 showed the lowest drilling temperatures with vibration assistance and a marked improvement in comparison with conventional drilling. The lowest obtained temperature using common drilling was obtained drilling Bone 5 and Bone 1, it was 46.8°C and 49.3°C respectively, which were still higher than that which were obtained with vibration assisted drilling, though the difference in this case could be said is negligible. The data for drilling Bone 2 and Bone 3, show that every mode overstepped the so called safe threshold of 50°C, even though it is only 1-3°C above it using vibration assistance, it could be said it is marked improvement in comparison with 9.8°C and 16.9°C above the threshold observed with conventional drilling.

Examining obtained drilling times of bone samples little to no correlation with drilling temperature could be found. It could be said that faster drilling times lead to lower obtained temperatures, but that would be shortsighted as the measured time obtained is with some measuring error. Compared to PMMA drilling, the times have increased 2-3 times, which makes sense as the compact bone being drilled was 2-3 times as thick as PMMA samples. Contrary to PMMA drilling experiment where some modes of vibration had positive, some negative effect, all vibration assisted modes had a positive impact both on drilling temperature and drilling time.

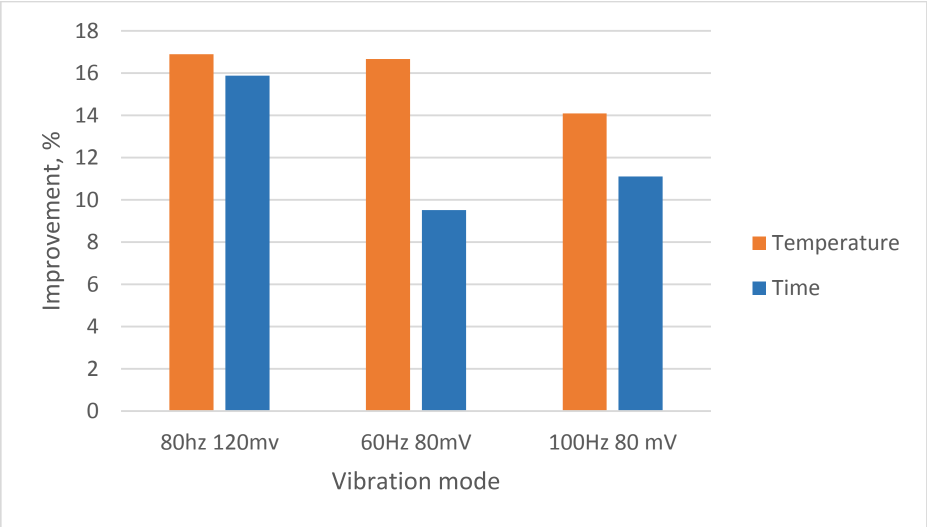


Fig. 23 Improvement of cutting parameters in the given vibration modes

Like in previous experiment, improvement of drilling parameters is calculated taking averages of obtained temperatures and times. It is observed that biggest improvement is obtained by vibrating the sample at 80Hz while oscilloscope shows signal of 120mV, though 60Hz at 80mV temperature vise is not far behind. All in all an improvement of at least 14% (temperature lower 14%), compared conventional drilling is a result worth discussion.

Examining drilling temperature averages does not show the whole picture, only scrutinizing every bit of data it is possible to see that some modes of vibration work better than others, and in some particular conditions vibration modes have no quantifiable effect. These peculiar results show that not all boundary conditions at the moment of the experiment are constant and consistent, some factors which are not taken into account may influence the obtained results.

3.4 Discussion regarding experiment number 2

Using proposed experimental setup an experiment which consisted of two distinct phases was designed and performed. First part consisted of PMMA drilling to obtain vibration modes which show the highest reduction in drilling temperature. In addition to sample at rest, three other modes were selected 80Hz 120mV, 60Hz 80mV 100Hz 80mV.

The second part of experiment dealt with drilling temperature of compact bone, applying selected modes of vibration to drilling, experimental data was obtained and analyzed. It was observed that drilling with vibration assistance it was possible to reduce drilling temperature on average by at least 14%.

In order to further the discussion regarding low frequency vibration assisted drilling of compact bone, main merits, drawbacks and solutions for these drawbacks, of this experimental setup are discussed.

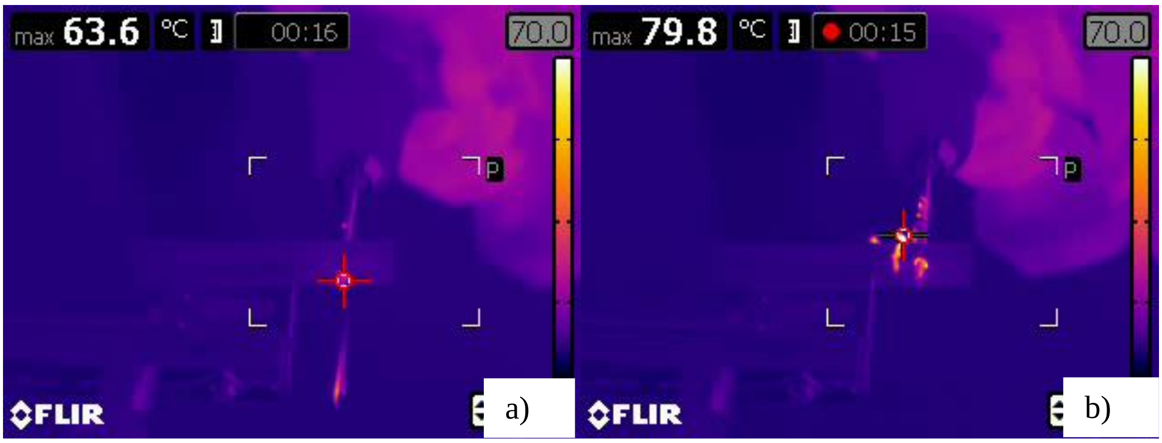


Fig. 24 Highest observed temperature a) Hole b) Chip

In principle measuring temperature with non-contact optical thermometer or thermographic camera at the exit hole is an interesting solution, especially when the drilling process takes only a few seconds and common thermocouples are too inert for this kind of temperature measurement.

To insure that samples are being vibrated at the same determined amplitude accelerometer is used. It is used to set comparable vibration amplitudes between different samples as can be seen in **Fig. 25**, actual amplitude is not important when using the same accelerometer.

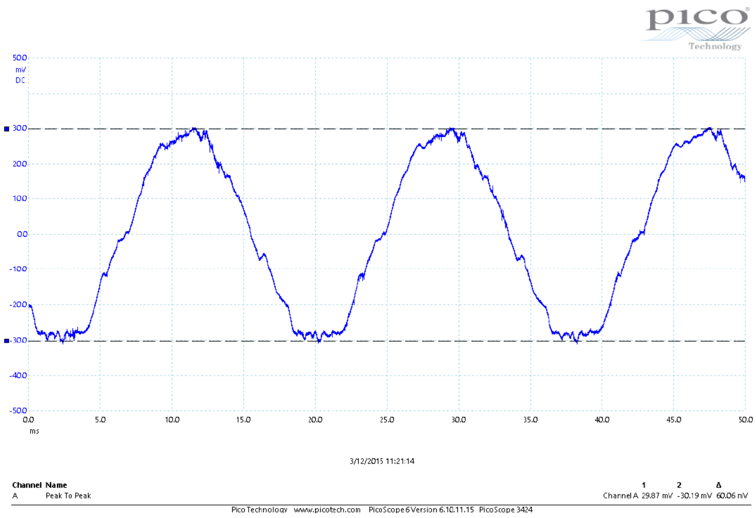


Fig. 25 Accelerometer readings (peak-to-peak 60mV)

Problems/Solutions:

The employed thermal camera is too inert to obtain accurate temperature histories for the drilling operation, it records new temperature reading every ¼ of a second. The camera cannot log temperatures as a simple text file, making it tedious extracting the relevant data. A high speed camera should be used, as an example FLIR A6750sc SLS which can capture up to 480 frames per second of thermographic data.

The used force sensor with its indicator cannot be connected to PC to log the applied force on the sample. Drilling operation was done by hand, author tried to apply a consistent force between various samples, but inconsistencies have occurred. Not having a log of applied force introduces uncertainty and reduces repeatability of the experiment. A force sensor which can log data should be utilized.

Drill speed with load and without is different. Drill speed under load is unknown, it is impossible to correlate it with vibration frequency. Hand drills usually have different free running speeds, compared to speeds under load. A custom speedometer could be employed to capture the relevant data.

In hindsight a cross section of rib bones should have been used so that only a single layer of compact bone would be drilled.

Having drilled the bones another cross section should have been made on the drilling hole to measure the amount of compact bone in that particular spot.

Should have used Ringer's solution for the bone transportation and in order to keep it moist. Not having done so, might have made bones dryer than they should be, which in turn might skew the results.

After reviewing recorded data it was deemed important to ignore highest obtained temperature if at the time the temperature is indicated on the chip (**Fig. 24** b)) , the material chip is made of is already discarded. Only the surface of the hole was taken into account, which might have led to some inconsistencies. The inertia of the camera was the main culprit of such situation, by having a faster reacting thermometer, or having more points for temperature measuring, it would be possible to easily ignore flying chips, and thus they would have little to no influence on the obtained data.

For future consideration of a similar investigation a more robust equipment should be utilized in order to improve the repeatability of the experiment. All the problems and solutions should be taken into account and be accounted for.

CONCLUSIONS

1. Bone drilling is influenced by drill properties (drill geometry, flute number, diameter), drilling parameters (revolutions per minute, feed rate), as well as bone condition, and type of bone.
2. Vibration assisted drilling is an effective method to drill materials that are otherwise hard to drill (be it too brittle, hard, prone to fracturing).
3. Drill speed of 1200rpm is the most widely used in conventional low speed drilling situations. Drill bits with diameter of 4.2 or lower are most commonly used in surgical orthopedic procedures.
4. Two experiments were designed and conducted. Observing drawbacks of the first experiment it was possible to design the second experiment with less uncertainty and higher repeatability.
5. Obtained data shows at least 14% reduction in drilling temperature of vibrated bone samples, as opposed to the conventionally drilled ones. Thermo-graphic imaging proved to be a viable if limited temperature measuring solution.

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ANNEX 1 EQUIPMENT TECHNICAL DATA

Signal Generator:	WW5064

Amplifier:	**VPA2100MN**
Power Supply max.	230VAC/50Hz
Output Power (stereo)	2 x 60Wrms/4Ω
2 x 50Wrms/8Ω	
Input connections	balanced XLR and phone jack
LED indication	SIGNAL, CLIP, POWER
Speaker connections	SCREW, BANANA PLUG
Fuse	F 3.15A 250VAC (5 x 20mm)
Total Weight	7.4kg
Dimensions	482 x 240 x 95mm
Max. Ambient Temperature	45°C

Electromagnetic vibrator:	VEB ROBOTRON MESS-ELEKTRONIK OTTO SHON

Drill:	**Makita 8391DWPE**
Max in Steel:	13mm
Max in Wood:	36mm
Max in Masonry:	13mm
No Load Speed:	H:0-1,200 L:0-400rpm
Max Torque:	27/42Nm
Net Weight:	2.3kg
Voltage:	18 volts
Total Shipping Weight:	4kg

Drill bit:	HSS DIN 338 Twist drill
Diameter, mm:	4.2
Total length, mm:	75
Flute Length, mm:	43

Thermal camera:	T450sc	
Resolution	320x240 pixels	
Thermal sensitivity	(at 30 °C)	<30 mK @ 30 °C
Field of view (FOV) / Minimum focus distance	25º x 19º / 0.4m	
Image frequency	60 Hz	
Spectral range	7.5 to 13 µm	
Spatial resolution	1.36 mrad	
Focus	Automatic (one shot) or manual	
Temperature range	-20 °C to +120 °C	
	0 °C to +650 °C	
	+250 °C to +1,500 °C	
Camera weight incl. battery	0.88 kg	
Camera size (L x W x H)	106 x 201 x 125 mm	

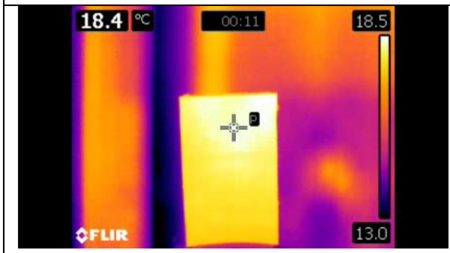
Accelerometer:	Schwingungsaufnehmer KD35	
Uebertragungsfaktor	5 mV/ms**-2, m = 25 g	
Sensitivity	50 mV/g	
Capacity of the pick-up with	1,5 m cable	1,4 nF
Resonance frequency	20 kHz	
Working frequency range	5 Hz … 5 kHz	
Insolation resistance	109 Ohm	
Transverse direction factor	≤ 5%	
Max. Acceleration	3000 m/s-2	
Material of the case	Aluminium	
Weight	28 Gramm	
Thread bore	M5	
Cable connection	seitlich / latera	

Osciloscope:	Picoscope 4226
Number of channels	2 BNC inputs
Analog bandwidth	50 MHz 100 MHz
Voltage ranges	±50 mV to ±20 V
Sensitivity	10 mV/div to 4 V/div
Vertical resolution	12 bits
Input coupling	AC or DC, software-selectable
Input impedance	1 MΩ ‖ 16 pF
Overload protection	±100 V
Sampling:	
Time base	100 ns/div to 200 s/div
Maximum sampling rate (real-time)	1 channel in use 125 MS/s
2 channels in use	125 MS/s
Maximum sampling rate (ETS)	10 GS/s
Buffer size	32 MS shared between active channels
Triggering Sources	Ch A, Ch B, Ext
Performance:	
Time base accuracy	50 ppm
DC accuracy	1% of full scale
Trigger resolution	1 LSB (Ch A, Ch B)
Trigger re-arm time	1 μs (fastest timebase, rapid trigger)
Environment:	
Temperature range Operating:	0 °C to 45 °C
For stated accuracy:	20 °C to 30 °C
PC connection	USB 2.0. Compatible with USB 1.1
PC operating system	Windows XP, Windows Vista or Windows 7
Power supply	5 V @ 500 mA max. from USB port
Dimensions	200 mm x 140 mm x 38 mm including connectors
Weight	< 500 g

Force sensor/indicator:	FORCE/TORQUE gauge MODEL BGI Mark-10
Sensor:	
Accuracy:	±0.15% of full scale + BGI
Safe overload:	150% of full scale
Model number:	SS200
Capacity x resolution:	100 x 0.05 kgF, 1000 x 0.5 N
Indicator:	
Accuracy:	±0.1% of full scale ±1 digit + sensor
Power:	AC or rechargeable battery with Intelligent Power Management System (IPM), a 3-step system that warns the user via a "LO BAT" indicator and then powers off the gauge.
Battery life:	8-10 hours of continuous use
Selectable units of measurement:	lb, kg, g, N, ozin, lbFin, kgFmm, kgFm, Ncm, Nm (depending on sensor)
Outputs:	
RS-232	Fully configurable up to 9600 baud. Includes Gauge Control Language (GCL) for full computer control of all functions.
Mitutoyo (Digimatic)	Serial BCD suitable for all Mitutoyo SPC-compatible devices
Analog	±1 VCD, ±0.25% of full scale at capacity. + CW, - for CCW.
General purpose I/O	Three open collector outputs and one input (utilizing Mitutoyo lines)
Set Points	Three open collector lines (utilizing Mitutoyo lines)
Configurable settings:	Analog filters, digital filters, RS-232, outputs selection (other than RS-232), automatic output (RS-232), automatic shutoff, initial (default), averaging mode, calibration.
Environmental requirements:	5°C - 45°C, <96% humidity (non-condensating)
Thermal effects:	Zero: 0.03% of full scale/°C, Span: 0.01% of full scale/°C for all remote sensors

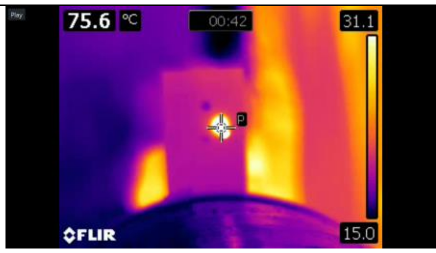
ANNEX 2 EXPERIMENT 1 PMMA DRILLING DATA

Ambient



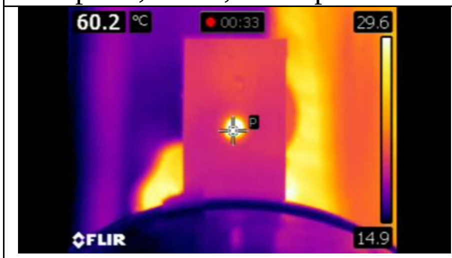
Time, s	-
T_{max}, °C	18.4

Sample 1, 0Hz, 1200rpm



Time, s	42
T_{max}, °C	75.6

Sample 2, 10Hz, 1200rpm



Time, s	33
T_{max}, °C	60.2

Sample 3, 20Hz, 1200rpm

Time, s	30
T_{max}, °C	62.6

Sample 4, 30Hz, 1200rpm

Time, s	32
T_{max}, °C	60.1

Sample 5, 40Hz, 1200rpm

Time, s	32
T_{max}, °C	61.4

Sample 6, 50Hz, 1200rpm

Time, s	34
T_{max}, °C	62.4

ANNEX 3 EXPERIMENT 2 PMMA DRILLING DATA

Vibration mode	time	temperature
0Hz 0mv	7	77
	7	68.8
	6	78.7
	9	80.9
	5	66.8
	4	73.2
	5	89.6
	5	81.7
	4	60.8
	5	66.7
Avarage	5.7	74.42
60Hz 40mV	6	69.5
	7	71.9
	6	74.3
	6	70.5
	6	65.8
	6	74.7
	6	65.8
	6	66.7
	6	85.1
	6	81.9
Avarage	6.1	76.08
80Hz 40mV	8	64.4
	6	75
	4	81.5
	5	66.4
	8	77.3
	7	81.7
	5	83.1
	6	67.2
	5	64.9
	6	74.8
Avarage	6	73.63
60Hz 80mV	5	73.3
	8	66.4
	7	69.2
	7	65.1
	7	66.2
	6	65.8
	7	68.9
	6	73.7
	7	69.1
	8	62.5
Avarage	6.8	68.02

Vibration mode	time	temperature
80Hz 80mV	6	80.9
	7	70.8
	6	62.6
	9	79
	8	65
	7	72.4
	8	77.4
	6	64.1
	8	80.1
	7	64.3
Avarage	7.2	71.66
100Hz 80mV	6	73.8
	7	50.3
	5	60
	8	57
	8	55.4
	4	49.8
	5	78.3
	5	75.1
	5	61.5
	6	61.4
Avarage	5.9	62.26
120Hz 80mV	6	63.2
	4	80.5
	4	76.1
	5	63.2
	4	80.5
	4	70.4
	5	68.8
	5	69.6
	5	79.3
	4	75.4
Avarage	4.6	72.7
140Hz 80mV	4	62.9
	5	83.9
	6	67.3
	6	71.9
	6	62.1
	5	67.7
	6	66.4
	5	78.9
	6	72.5
	5	62.6
Avarage	5.4	69.62

Vibration mode	time	temperature
80Hz 120mV	5	54.6
	4	59.7
	4	50.5
	4	50
	5	45
	4	63.6
	5	54.6
	4	52.6
	4	52.4
	4	53.6
Avarage	4.3	53.66