Experimental Investigations into Assessment of Thrust Force and Temperature in Bone Drilling

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Research Article

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Abstract

Drilling of bone is a challenging task for surgeons due to its effect on bone tissues. During drilling, it is noted that the temperature of bone increases. This increase in temperature if above 47°C causes thermal necrosis. Experiments were conducted to study the effect of input drilling parameters and drill bit parameters on bone health. To plan experiments a full factorial design method was used. An analysis is done on the effect of input parameters on thrust force and temperature of bone. The analysis of results shows an increase in thrust force and temperature when the feed rate increases and the spindle speed decreases. Further, the analysis of results shows an increase in thrust force and temperature when point angle increases and helix angle decreases. The increase in thrust force results in temperature rise. Scanning electron microscopy is done to analyze the surface topography of drilled hole. SEM image analysis shows an increase micro-crack in the drilled area when the thrust force and temperature increases.

1. Introduction

In the human body bone is an important part. The inner part of bone is a cancellous bone and it is soft. The outer part of the bone is a cortical bone and it is hard. The microstructure of the bone is very complex and it possesses properties like self-healing [1].

Due to accidents and age problems bone fracture became a day-to-day issue. When a bone is broken because of its self-healing property, it provides new forming cells which help in the recovery of the fractured bone. The fracture of the bone is usually repaired by drilling it at the required location for inserting screw and fixing of plates [2]. Drilling thrust force and temperature are the two important parameters that affect the bone drilling process. Drilled holes require a high degree stability to ensure that the screws grip the holes firmly. High drilling temperature and thrust force result in thermal necrosis and cracks in the bone which badly affects the recovery of bone [3] [4]. Further excessive rise in temperature around a drill site (over 47 °C) will cause thermal necrosis [5] [6]. Many factors increase drilling temperature and thrust force like characteristics of the bone, cortical thickness of bone [6], drill bit geometry parameters [7] [8] [9] [10] low bone thermal conductivity [11], cutting speeds and feed rates [12] [13]. Improved drill design [14] [15] comparing experiments [7] and bone drilling system [16] were presented to avoid unnecessary damage to soft tissue, minimize invasion or detect a breakthrough. The important parameters of drill bit that influence bone drilling thrust force are point angle, flutes [17], drill bit diameter, drilling speed and feed rate [8]. Several researchers have reported drill bit geometry parameters are responsible for an increase in thermal necrosis of bone [18]. Studies have been done on the bone drilling process to find out the effects of the drill bit diameter on the temperature of bone while drilling [8] [10]. Augustin [8] and Kalinandi [10] reported that the diameter of the drill bit is the most influencing parameter which increases the drilling temperature of bone. In the case of a surgical drill, depending upon the drill diameter the range of 13º-35º helix angle is generally used. For performing a drilling operation, the optimal helix angle of 27º is recommended by Farnworth and Burton [19]. In the past, various research has been done to find out the effect of a drill point angle on bone drilling. But there are no common results on the optimum drill point angle for bone drilling. After investigation, a 90º of point angle is recommended for surgical drills by Jacobs and Berry [20]. According to Farnworth and Burton [19] to get satisfactory performance in bone drilling operation the point angle in the range of 120º-140º is most suitable. Davidson and James [11] investigated the range of 100º to 160º is an optimal point angle range with large helix angles while bone drilling.

Past studies suggested various drill bit geometries and drilling parameters, but there is no common conclusion about an optimum value that can reduce the thermal necrosis of bone. So, this study is mainly based on determining the effect of drilling parameters and drill bit geometry parameters on thrust force and temperature in bone drilling.

2. Material And Methods

2.1 Materials

The specimen used for experimental work was caprine femur bone, which resembles similar characteristics of the human bone. The specimen was prepared by sectioning the femur using a knife. The specimen was cleaned using saline solution. Primary holes were drilled in the bone for thermocouple insertion. The specimens were preserved in a Deep Freezer under low temperature (-40ºC). A fixture made using a FDM machine was prepared to hold the specimen firmly during a drilling operation. The material of the fixture is ABS (Acrylonitrile-Butadiene-Styrene). A groove is provided in the fixture at the middle to fit a variable size of the bone. Clamps were also provided for holding the bone while bone drilling. A HAAS CNC milling machine is used for bone drilling. SS 304 drill bits were used as surgical drills. In this experiment, the diameter of a drill bit is kept constant i.e., 3.2 mm because many surgeons and researchers have used a drill bit diameter of 3.2 mm for femur bone [21].

A piezoelectric type Kistler cutting force dynamometer (9257 BA) was used to measure the thrust force. It has a built-in charge amplifier (Model-2825 A) with control unit type 5233. The online forces were measured using Dynoware software. For acquiring the data 500Hz sampling rate was used. The measurement of temperature is done using K type thermocouple and continuous temperature is acquired using the NI data acquisition (NI 9201) system. A Lab VIEW program has been developed for data acquisition. The overview of the experimental set-up with the work unit and fixture is shown in Fig. 1.

2.2 Experimental Methodology

To check the effect of various bone drilling parameters on thrust force and temperature, a series of experiments were conducted. Experiments were conducted on a CNC milling machine. Caprine femur bone was used as a specimen for conducting experiments. The schematic diagram of the experimental setup is shown in Fig. 2.

The output parameters were drilling thrust force and temperature rise. The selected input parameters and their levels are shown in Table 1.

TABLE I INPUT PARAMETERS AND THEIR LEVELS [21]

Input parameters	Levels				
	1	2	3	4	5
Spindle Speed (rpm)	400	800	1200	1600	2000
Feed rate (mm/rev)	0.04	0.06	0.08	0.10	0.12
Point angle (º)	70	80	90	100	110
Helix angle (º)	10	15	20	25	-

First of all, experiments were conducted to see the effect of spindle speed and feed rate on thrust force and temperature. A full factorial design method (5x5) was used and a total of 25 experiments were conducted. These are further replicated twice. Optimum parameters were selected based on minimum temperature generation. These drilling parameters are kept constant for the next experimentation. Further experiments were conducted to study the effect of point angle and helix angle on thrust force and temperature. Similarly, a full factorial design (5x4) was used and a total of 20 experiments were conducted. The experiments were replicated twice. The results of these experiments are used to decide optimum drill bit geometry parameters [21].

3. Results And Discussion

This section describes the results and analysis of experimental data gathered during bone drilling experiments. The analysis is supported by a graphical representation of the magnitude of output variables with respect to input parameters. The analysis is performed using the ANOVA technique. Graphs showing the variation in thrust force and temperature rise is presented in Fig. 3 and Fig. 4. Experimental thrust force vs time and temperature vs time graph obtained is shown in Fig. 3 and Fig. 4. After the initial contact, the force slowly increased with time and attained a peak height when the drill tip was in full contact with the bone. Due to the high sensitivity of the measurement system and vibrations in drilling equipment, small oscillations were recorded at peak values. The force suddenly drops when the drill penetrated the cancellous area of bone.

The graph presented in Fig. 3 and Fig. 4 shows thrust force (F_Z) and temperature as a function of time. The nature of thrust force in the cancellous bone and cortical bone region is also shown.

3.1 Analysis of Thrust force

1) Effect of spindle speed on thrust force: Fig. 5 shows the effect of spindle speed on thrust force at a constant feed rate. It was noted that when the spindle speed increases from 400 rpm to 2000 rpm; the thrust force decreases. It was observed that at 400 rpm spindle speed, the highest thrust force was required which is further reduced by 59.84 % at 2000 rpm. The decrease in thrust force with an increase in spindle speed is because of the decrease of mean friction coefficient at higher spindle speed [1].

2) Effect of feed rate on thrust force: Figure 6 shows the effect of a feed rate on thrust force at constant spindle speed. In this case as the feed rate increases, thrust force also increases. It is observed that at a 0.04 mm/rev feed rate lowest thrust force is required and it reaches the highest value at a 0.12 mm/rev feed rate. This can be explained by the fact that for larger values of feed rate, the proportionally greater force has to be applied in order to remove work material accumulated in front of the cutting edge.

3) Effect of point angle on thrust force: Figure 7 shows the effect of point angle on thrust force at a constant helix angle. From the results and graph, it is observed that as the point angle increases, thrust force also increases. At a point angle of 70º, the lowest thrust force was recorded and at a point angle of 110º, the highest thrust force was recorded. The smaller point angle produces a sharper tip which can easily penetrate into the material and requires less thrust force and a smaller point angle also prevents walking of the drill. The larger point angle induces higher shear deformations to the material resulting rise in thrust force.

4) Effect of the helix angle on thrust force: Figure 8 shows the effect of the helix angle on thrust force at a constant point angle. From the results and graph, it is observed that when the helix angle increases, thrust force decreases. At a helix angle of 10º, the highest thrust force was recorded and at a helix angle of 25º, the lowest thrust force was recorded. During orthopaedic treatment, bone is wet, therefore the chips produced get clogged when a small helix angle is used which increases friction and results in a higher amount of thrust force.

3.2 Analysis of Temperature

1) Effect of spindle speed on Temperature: Figure 9 represents the effect of spindle speed on the temperature at a constant feed rate. It is noted from the graph that as the spindle speed increases, temperature decreases. At a spindle speed of 400 rpm, the highest temperature was recorded and which is further reduced at a spindle speed of 2000 rpm. As spindle speed increases, thrust force decreases because of the reduced value of a mean coefficient of friction. As a result, the bone temperature decreased.

2) Effect of feed rate on Temperature: Figure 10 shows the effect of feed rate on the temperature at constant spindle speed. Temperature rise is linearly increased with the increase in feed rate. At 0.04 mm/rev feed rate, the temperature is the lowest but at 0.12 mm/rev the highest temperature was recorded. Higher feed rates cause higher thrust force due to more amount of material removal per unit time.

3) Effect of point angle on Temperature: The effect of point angle on the temperature at a constant helix angle is presented in Figure 11. From the graph, it is noticed that as the point angle increases temperature also increases. At a point angle of 70º, the lowest temperature is produced which is then increased at a point angle of 110º. A Small point angle has a more acute tip which can easily stab into the bone and less thrust force is required to drill resulting in less heat generation.

4) Effect of helix angle on Temperature: Figure 12 shows the effect of helix angle on the temperature at a constant point angle. From the graph, it is seen that as the helix angle increases, temperature decreases. At a helix angle of 10º, the highest temperature is generated and for the helix angle of 25º, the lowest temperature was recorded. Chips get clogged when a small helix angle is used. Clogged chips exert more friction while bone drilling which resulted in more heat generation in bone.

3.3 SEM analysis of bone

The drilled hole of bone is studied under the scanning electron microscope to find the micro-cracks if any. The effect of the drilling thrust force and temperature rise on bone can be compared using SEM images. It is observed that the higher thrust force causes an increase in micro-cracks in bone. However, the temperature rise causes burr formation on the drilled hole surface wall.

1) At feed rate 0.04 mm/rev and spindle speed 2000 rpm: Figure 13 (a) and (b) shows SEM images of bone drilled at the spindle speed of 2000 rpm and feed rate of 0.04 mm/rev. It is seen that microcrack is absent on the hole wall surface region because of the lower thrust force and temperature produced at this experimental analysis.

2) At feed rate 0.08 mm/rev and spindle speed 1200 rpm: Figure 14 (a) and (b) shows SEM images of bone that are drilled at a feed rate of 0.08 mm/rev and spindle speed of 1200 rpm. In this case, the microcrack is present near the hole surface region.

3)Feed rate 0.12 mm/rev and spindle speed 400 rpm: Figure 15 (a) and (b) shows SEM images of bone drilled at a feed rate of 0.12 mm/rev and spindle speed of 400 rpm. From the SEM image, we can see more micro-cracks near the drilled area and a poor surface finish of the drilled wall.

4) At helix angle 25º and point angle 70º: Figure 16 (a) and (b) shows SEM images of bone drilled at a helix angle of 25º and point angle of 70º. The hole drilled with the experimental condition is shown in fig. 20. The micro-cracks are evident at the hole wall surface region. Except for the micro crack at a few locations the remaining surface topography is fairly good.

5) At Point angle 90º and helix angle 15º (Intermediate condition): Figure 17 (a) and (b) shows SEM images of bone which are drilled at a helix angle of 15º and point angle of 90º. The output results of this experiment were; thrust force 96.9 N and temperature 38.71ºC. From the SEM image, it is observed that there are few micro-cracks near the drilled area.

6) At helix angle 10º and point angle 110º: Figure 18 (a) and (b) shows SEM images of bone that are drilled at a helix angle of 10º and point angle of 110º. The output results of this experiment are, thrust force 101.51 N and temperature of 44.29ºC. From the SEM image, we can observe that the built-up edge formation of chips around the drilled area is evident and the surface finish of the hole wall surface is poor.

4. Conclusion

The bone drilling process was studied by measuring thrust force and temperature rise with varying drilling parameters and drill bit geometry parameters. SEM image analysis of the drilled holes was done to observe the micro crack in a drilled bone. Following conclusions are drawn accordingly.

1. At higher spindle speed (2000 rpm) less amount of heat is generated due to the lower value of thrust forces.
2. At a higher feed rate, thrust force increases resulting in more amount of heat generation which results in thermal necrosis. Hence it is recommended to use the lowest feed rate, i.e., 0.04 mm/rev to avoid the thermal necrosis problem and also to avoid micro-cracks in the drilled area.
3. A higher point angle drill produces more thrust force and hence larger heat generation. It is found that the 70º-point angle drill facilitates easy penetration of drill into bone and hence reduces the amount of heat produced.
4. By increasing the helix angle, thrust force decreases resulting in less heat generation. Thus, it is recommended to use a higher helix angle drill preferably 25º. It avoids clogging of the drill bit which produces more friction while bone drilling.
5. From the SEM image analysis, it is concluded that as the thrust force increases, more microcracks develop in the area near to drilled hole. As the temperature increases, a poor surface finish was observed.

Declarations

Acknowledgements

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Figures

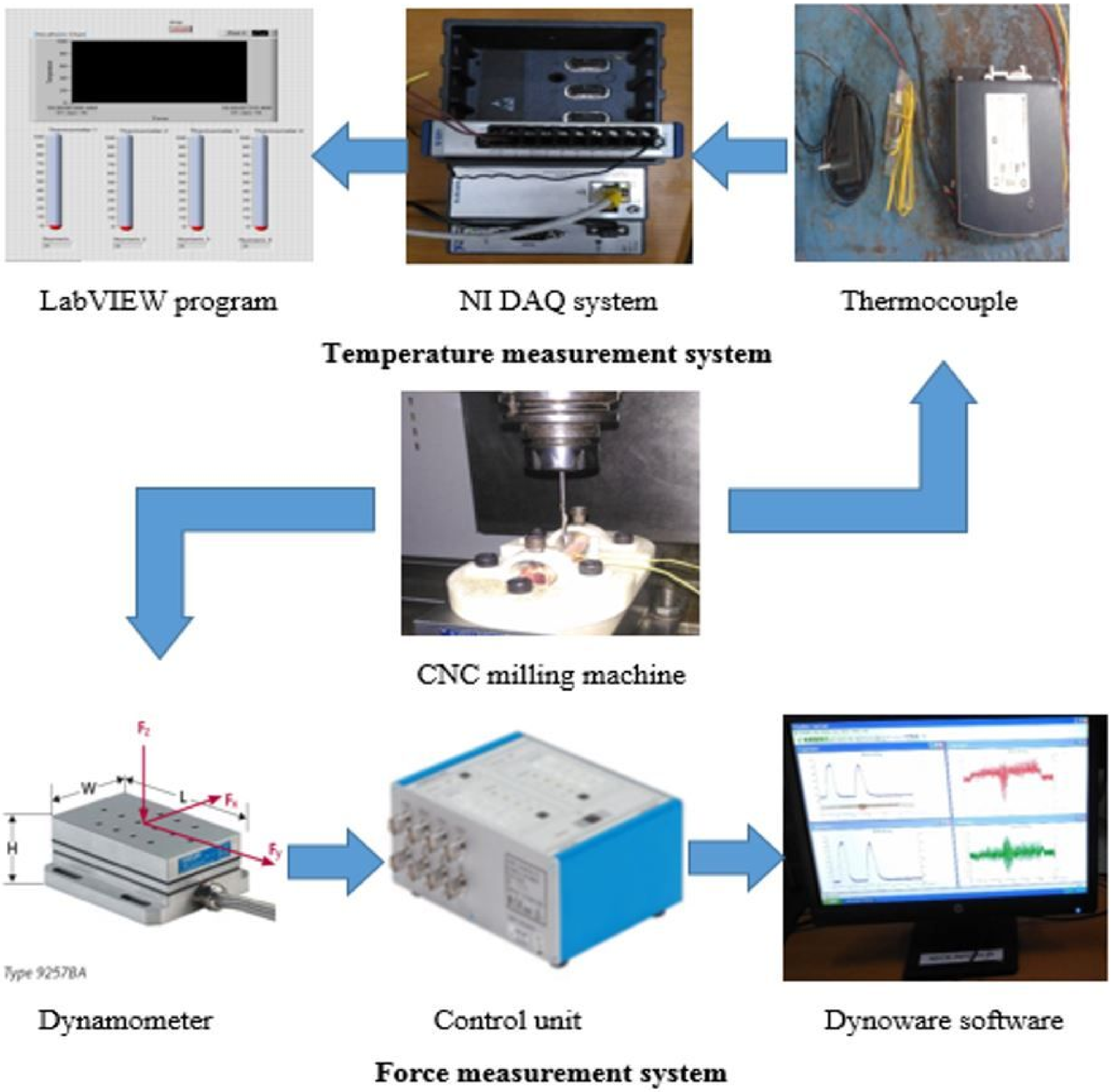


Figure 1

Experimental components

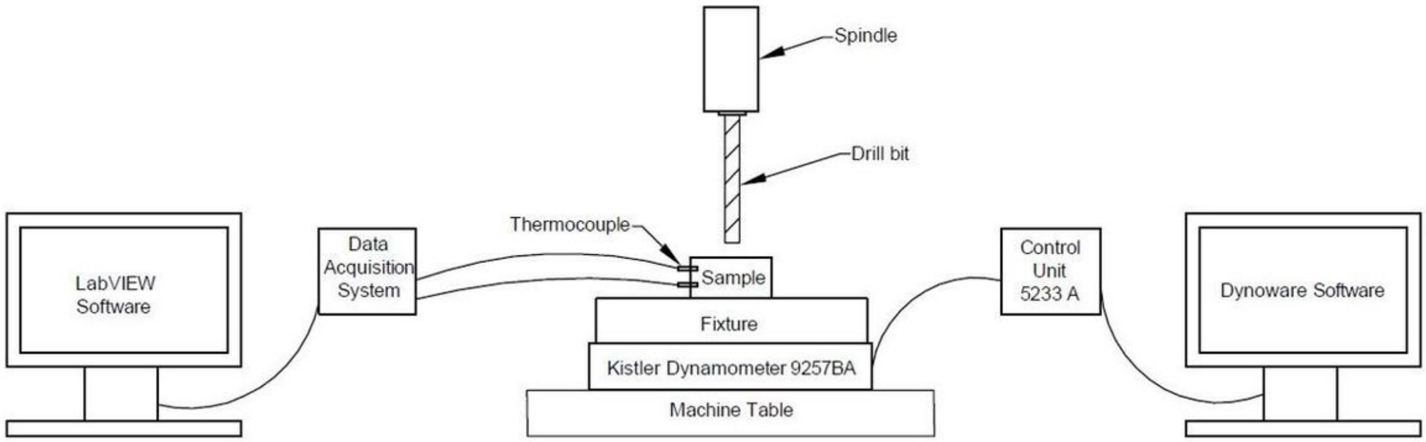


Figure 2

Experimental set up [21]

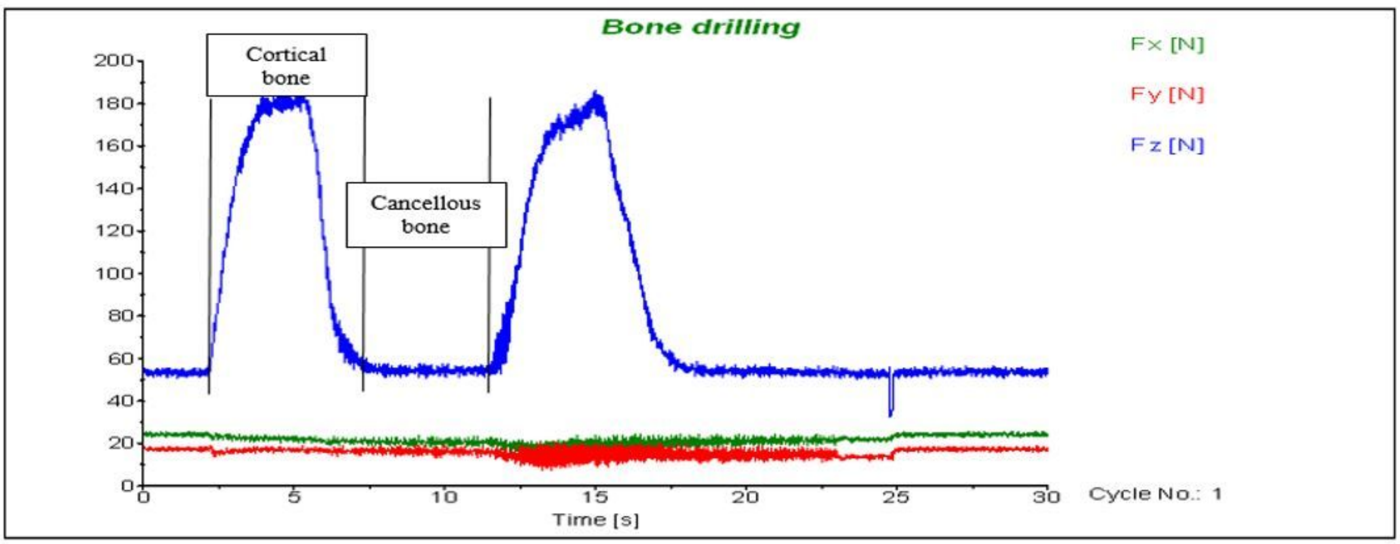


Figure 3

Thrust force (N) vs time (Sec) (Helix angle 10º and Point angle 110º)

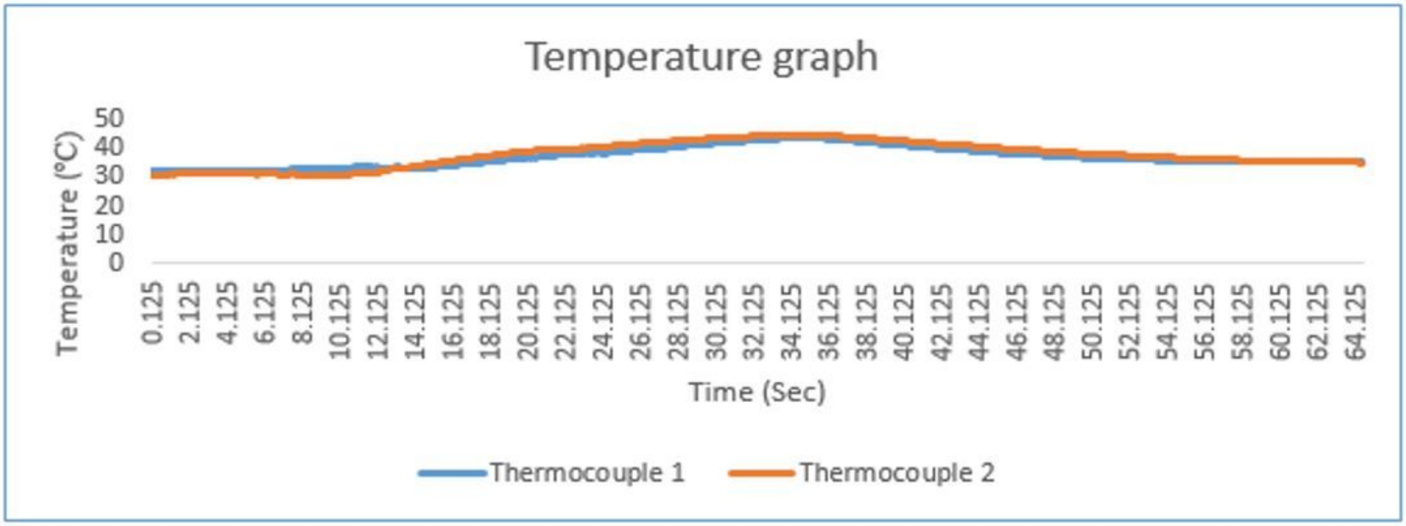


Figure 4

Temperature vs Time (Feed rate 0.1 mm/rev and spindle speed 400 rpm)

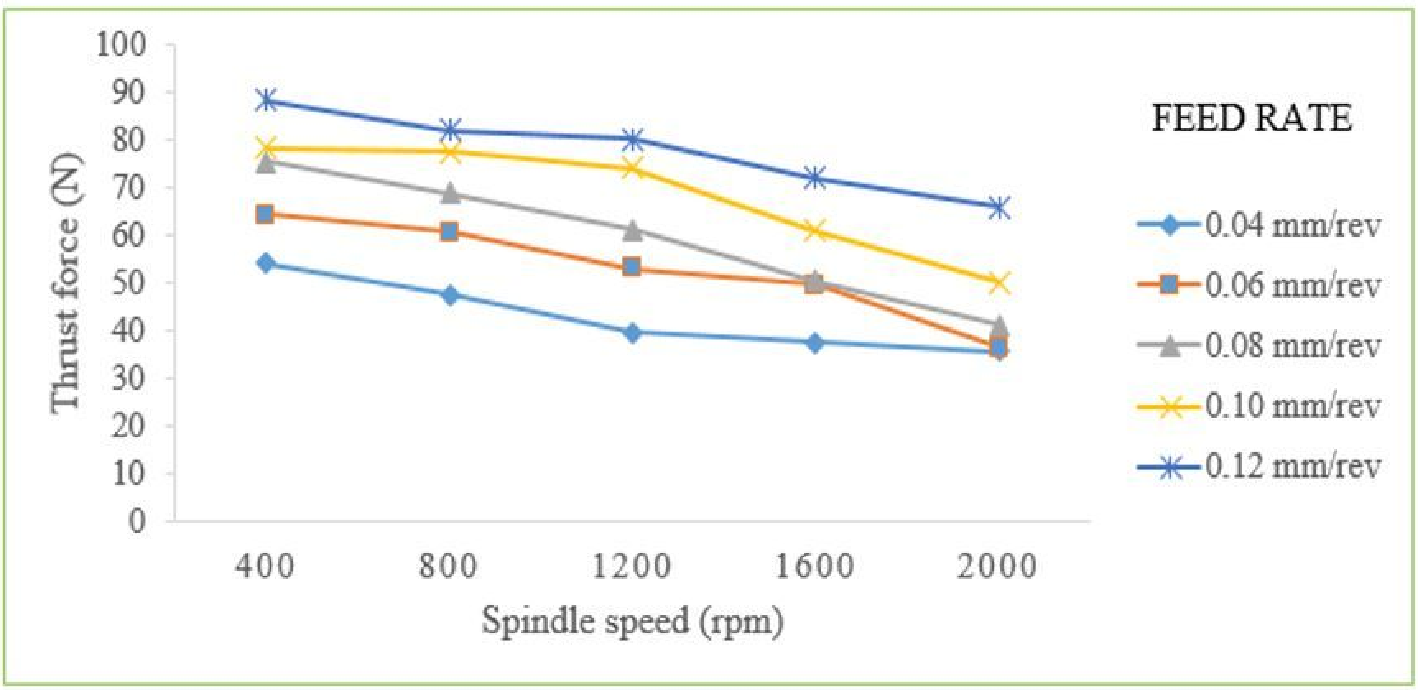


Figure 5

Effect of spindle speed on thrust force

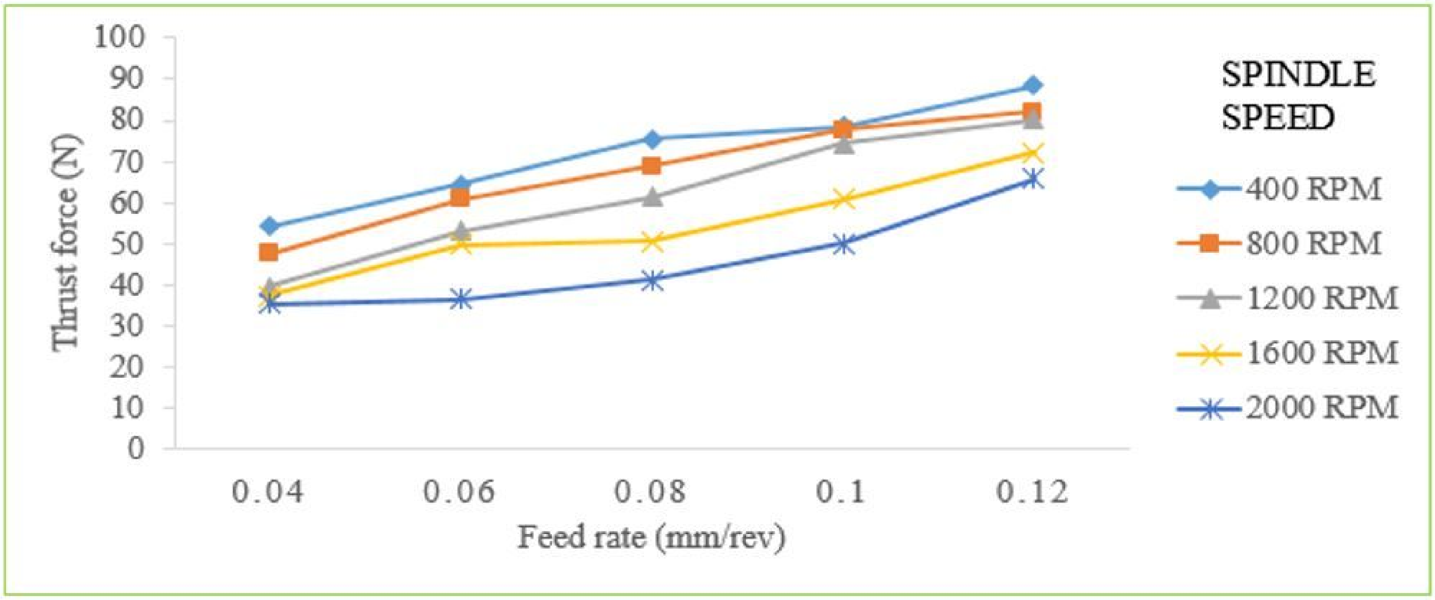


Figure 6

Effect of feed rate on thrust force

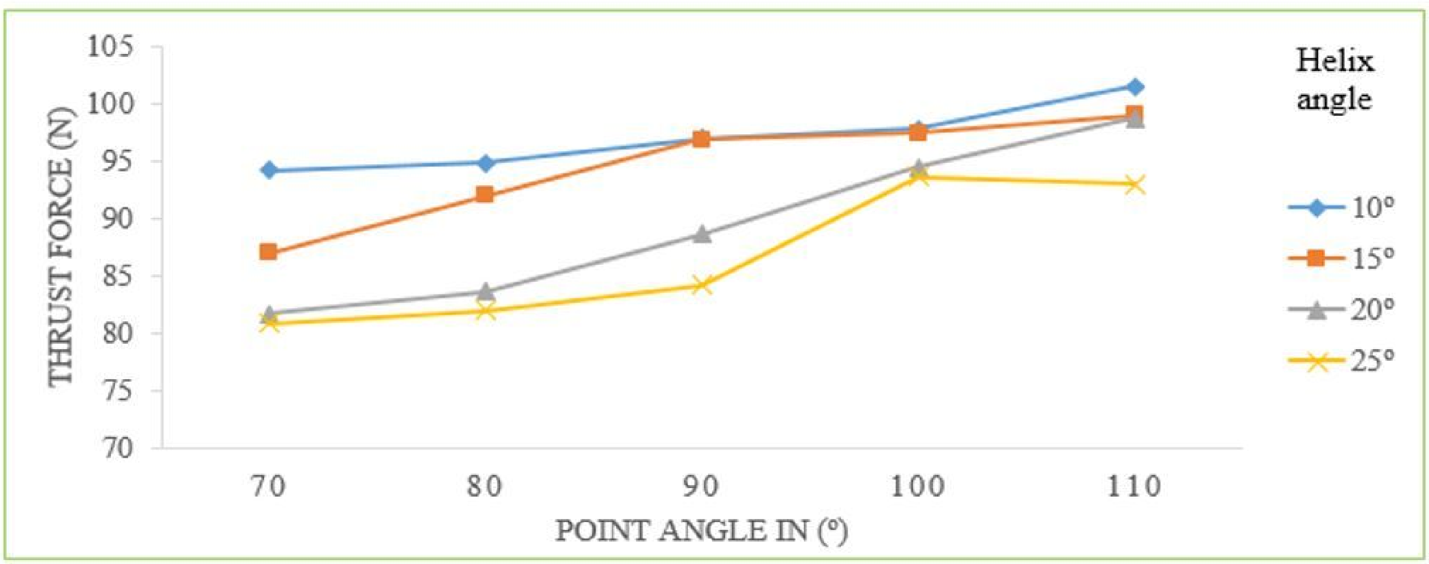


Figure 7

Effect of point angle on thrust force

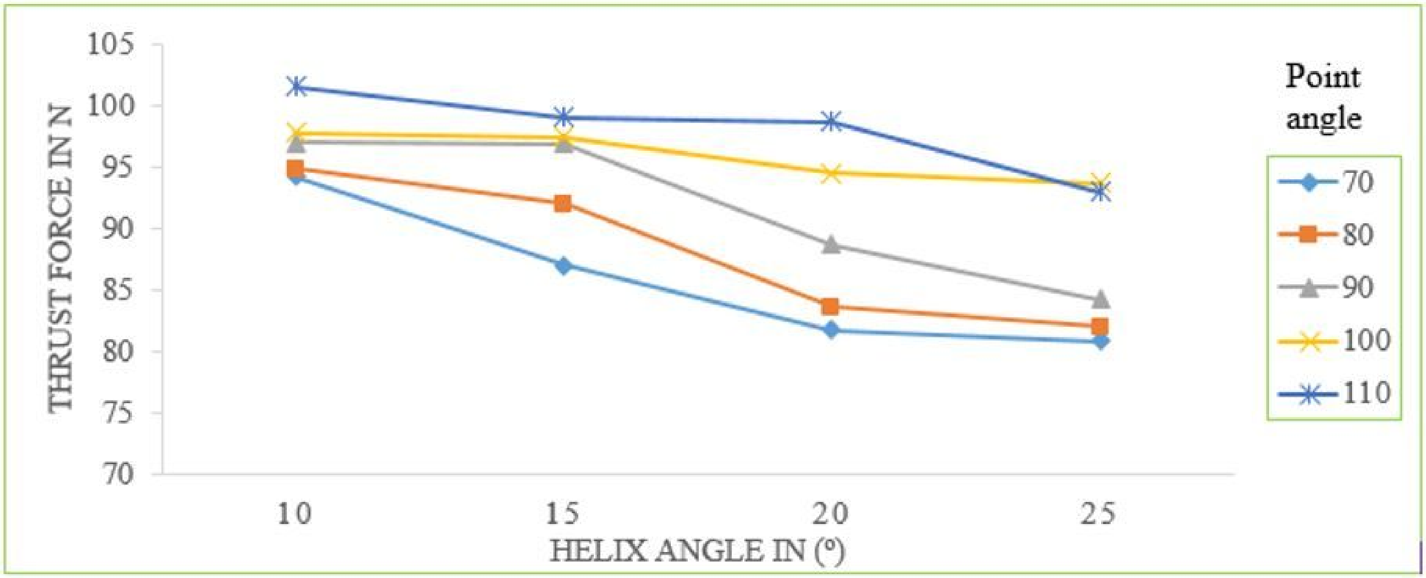


Figure 8

Effect of helix angle on thrust force

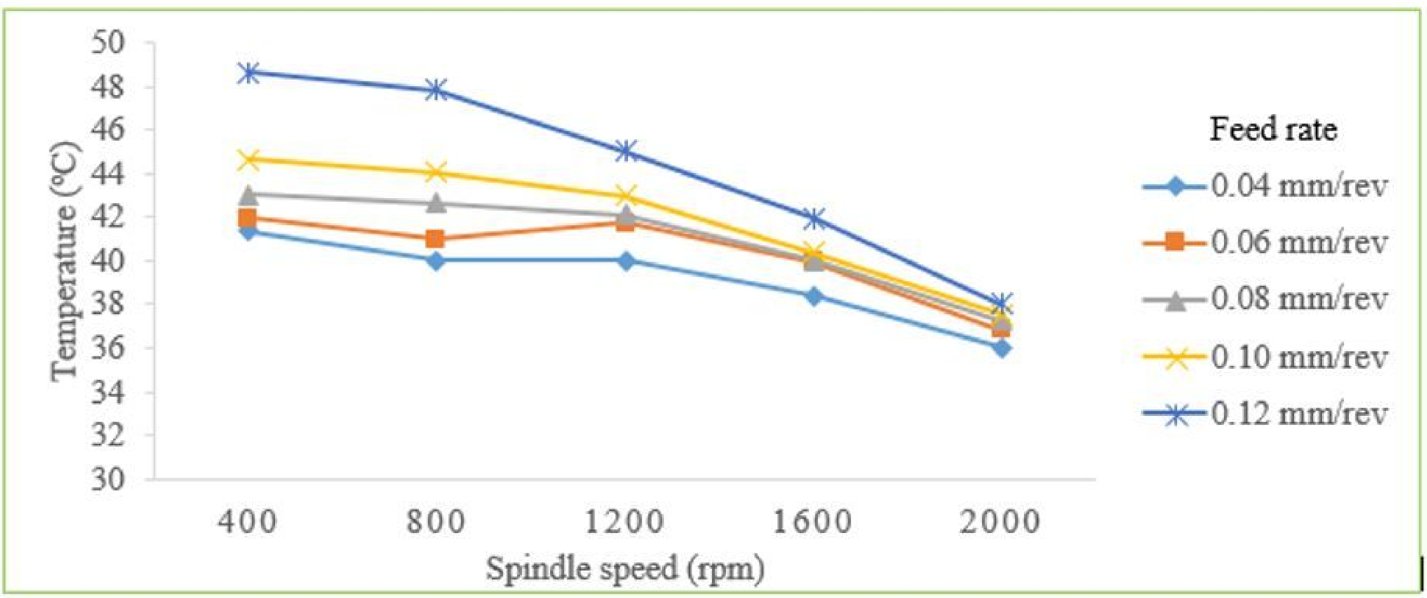


Figure 9

Effect of spindle speed on temperature

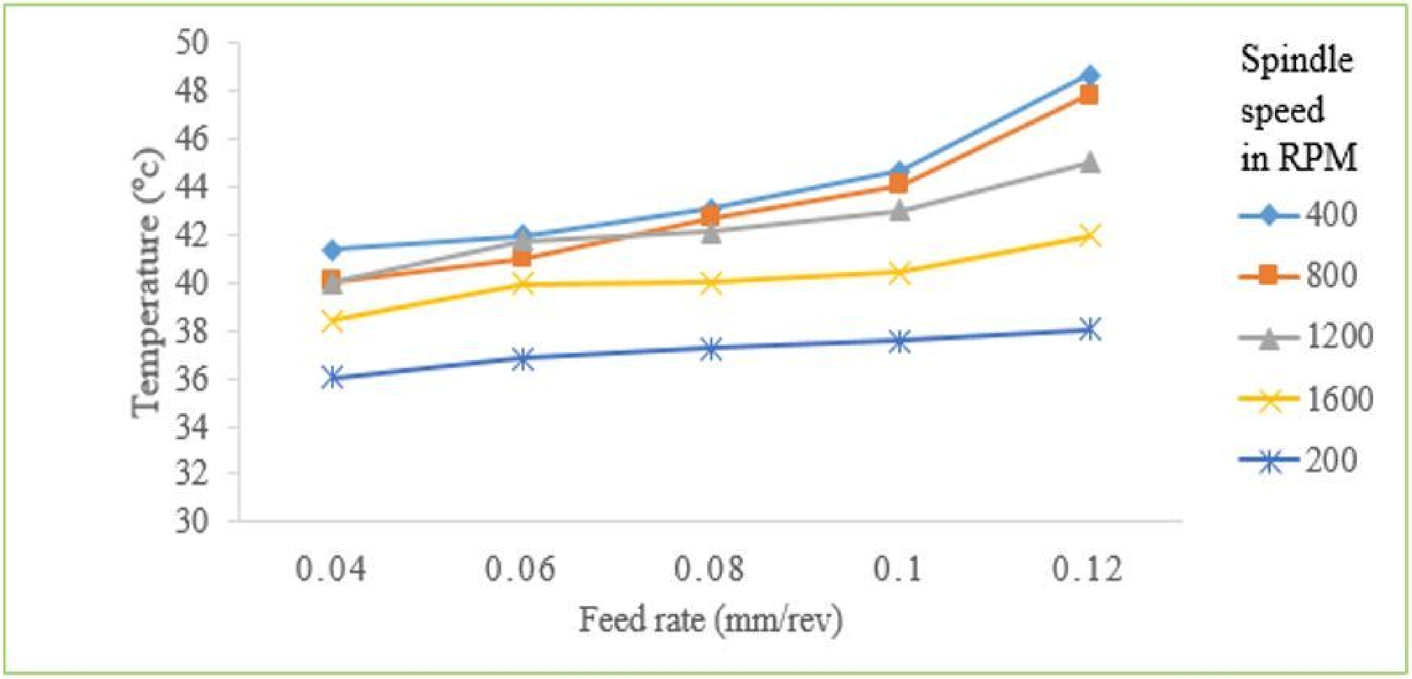


Figure 10

Effect of feed rate on temperature

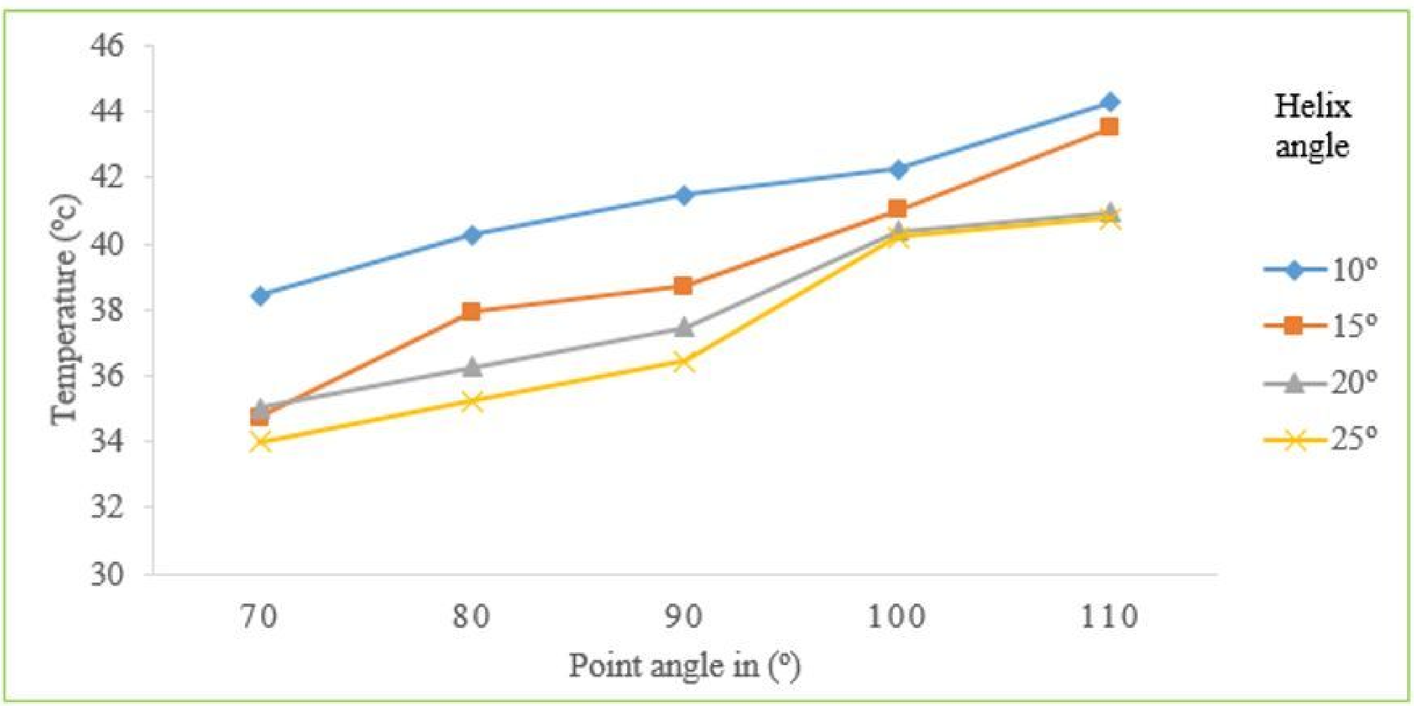


Figure 11

Effect of point angle on temperature

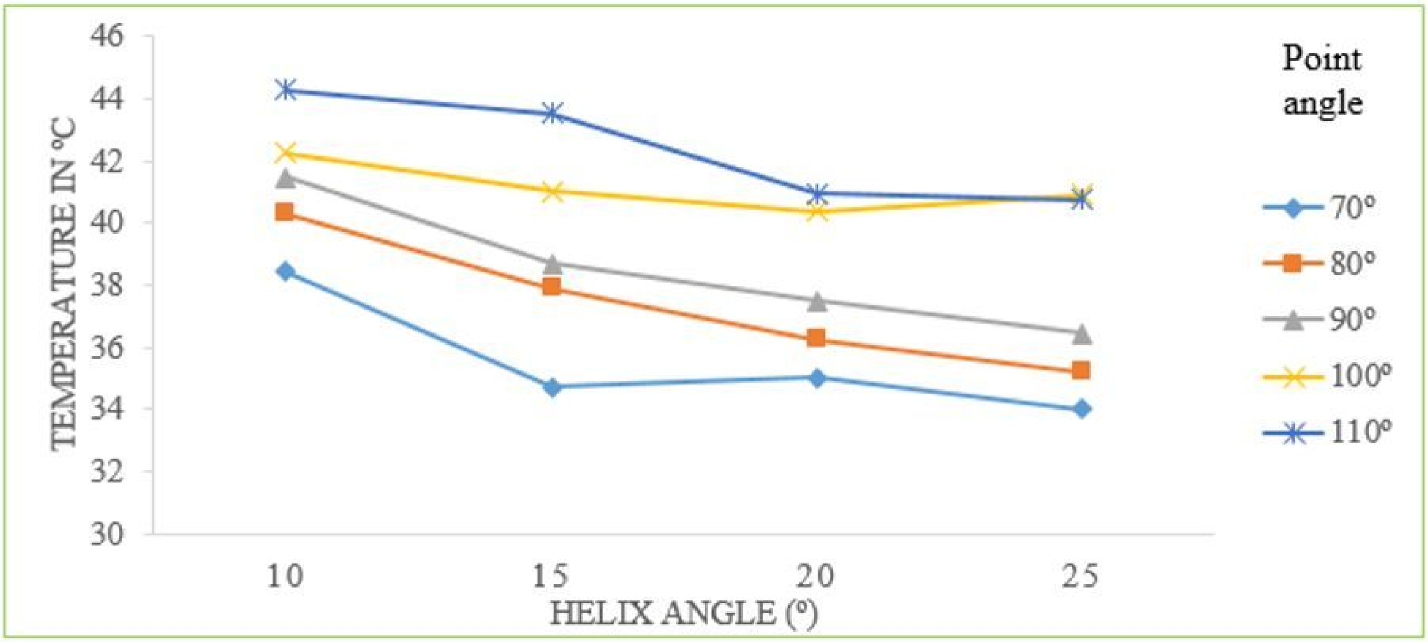


Figure 12

Effect of helix angle on temperature

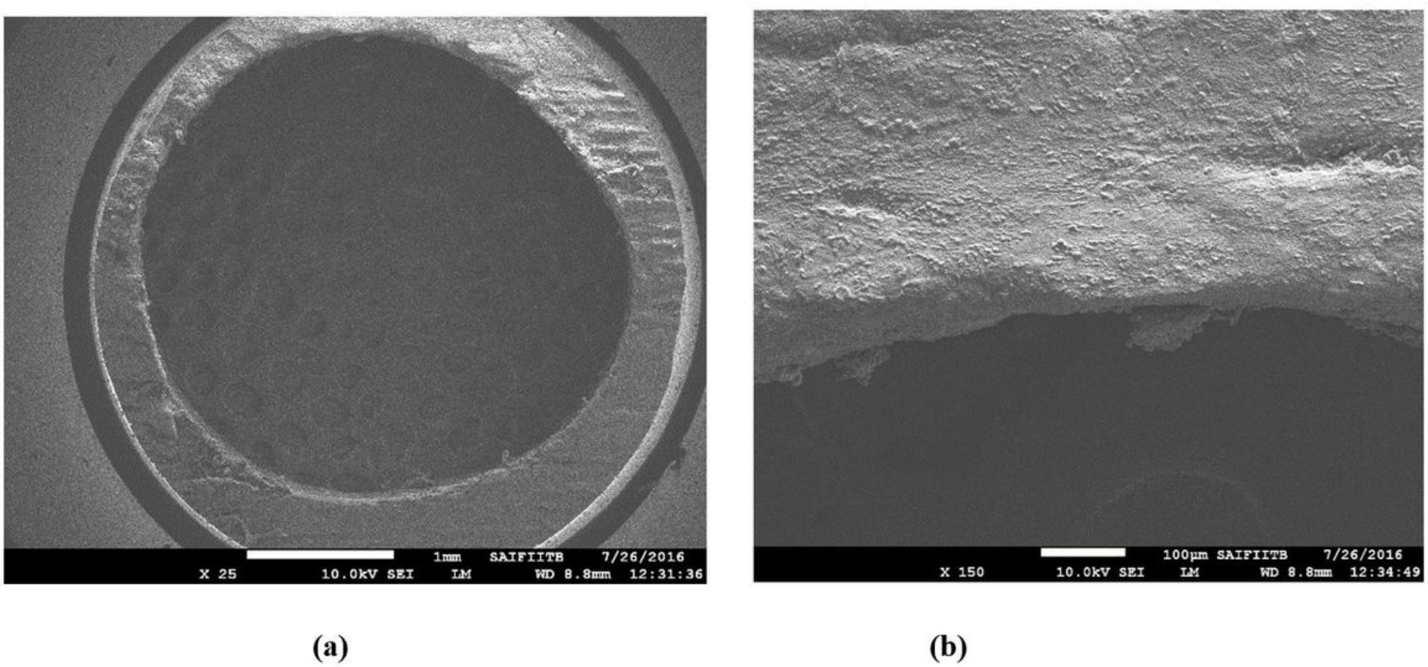
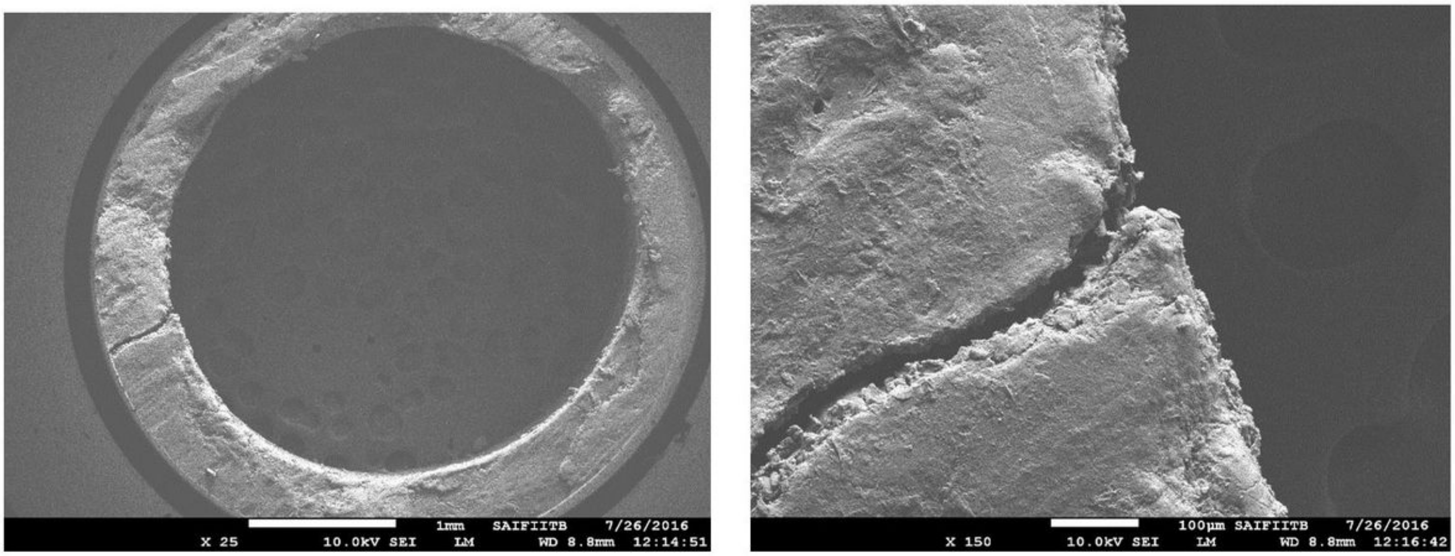


Figure 13

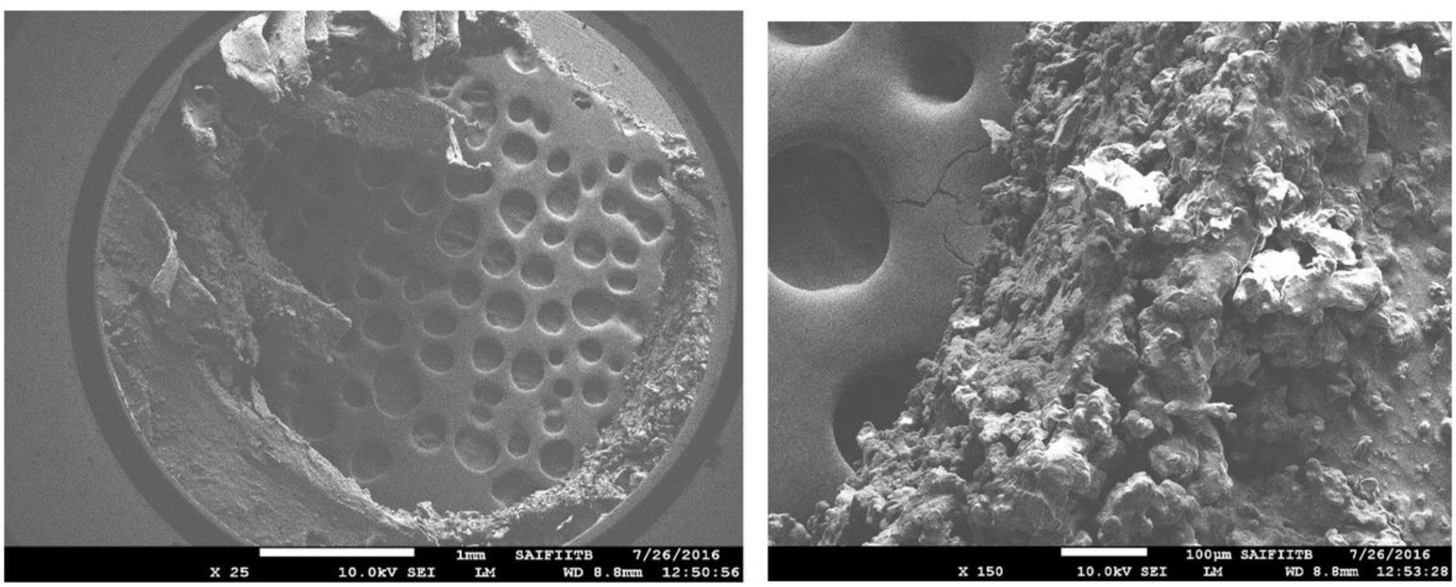
SEM images at (a) 25X (b) 150X (Feed rate 0.04 mm/rev and spindle speed 2000 rpm) (Thrust force = N Temperature = ºC)



(a) (b)

Figure 14

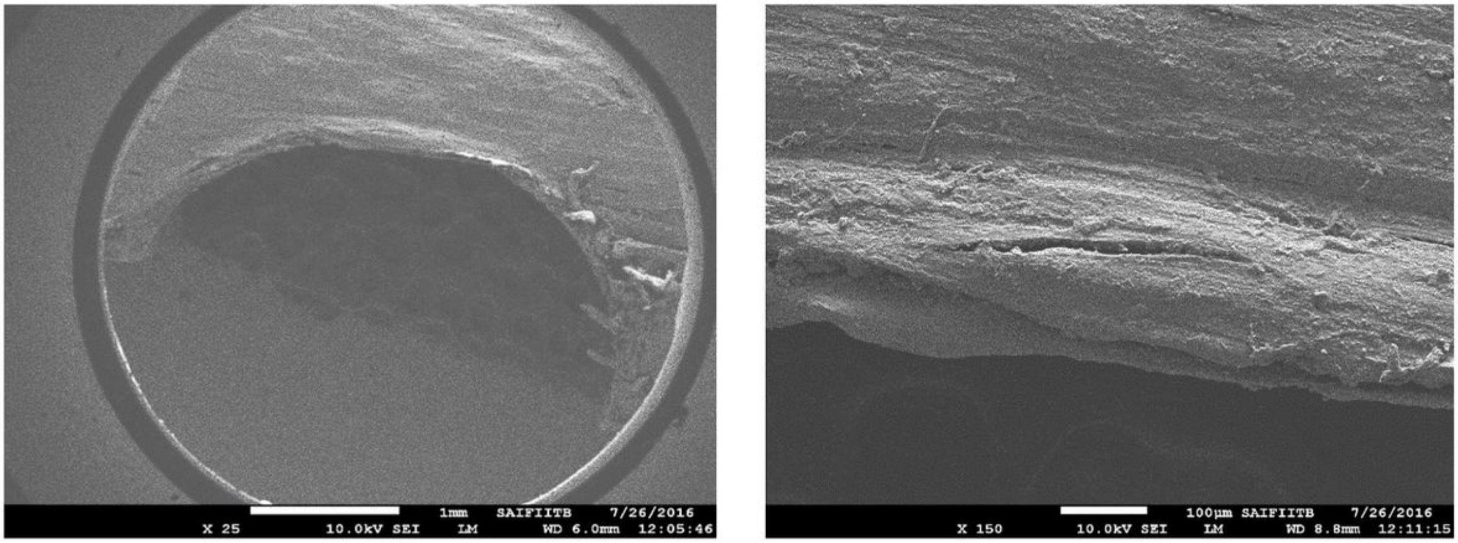
SEM images at (a) 25X (b) 150X (Spindle speed 1200 rpm and feed rate 0.08 mm/rev) (Thrust force = N, Temperature = ºC)



(a) (b)

Figure 15

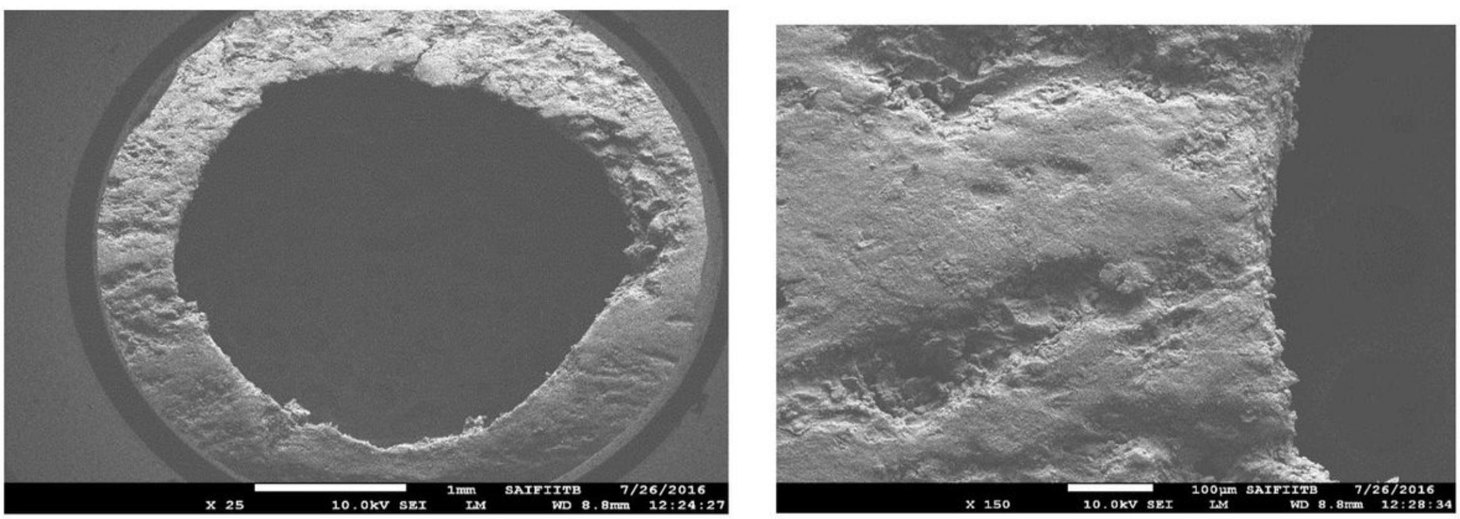
SEM images at (a) 25X (b) 150X (Feed rate 0.12 mm/rev and Spindle speed 400 rpm)



(a) (b)

Figure 16

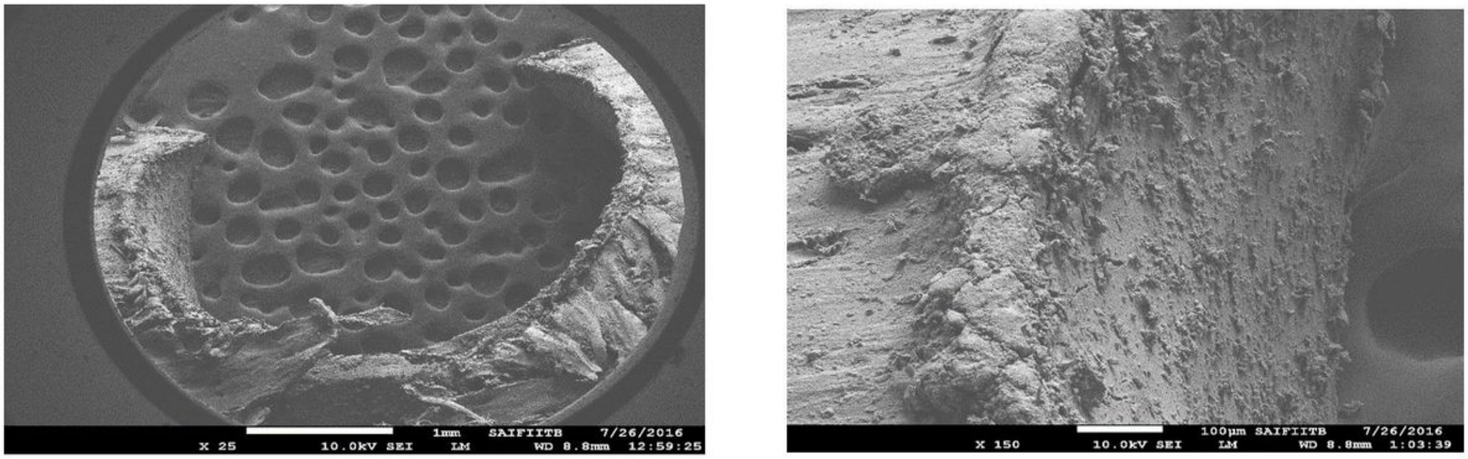
SEM images at (a) 25X (b) 150X (Helix angle 25º and point angle 70º)



(a) (b)

Figure 17

SEM images at (a) 25X (b) 150X (Helix angle 15º and Point angle 90º)



(a) (b)

Figure 18

SEM images at (a) 25X (b) 150X (Point angle 110º and helix angle 10º)