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Thermal Behavior of Self-Propelled Rotary Tool in Machining AISI 4140 Hardened Steel

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Abstract: This paper presents an experimental investigation into the thermal behavior of Self-Propelled Rotary Tool (SPRT) in turning difficult-to-cut material AISI 4140 hardened steel under dry condition. The experimental results were used to explain the influence of tilting angles of SPRT on thermal behavior of cutting tool. When changing the tilting angle from 25° to 35° the results show a significant difference in thermal behavior of the cutting tool such as tool temperature was reduced by 5.49 % as a result of spinning action. Further increases of tilting angle increases contact length and spinning speed, and thus reduced the effective cooling time per one revolution for non-contact/contact portion of the cutting tool. Finally, a comparison was made between SPRT and fixed tool (FT), which revealed that the use of SPRT is preferable to reduce the temperature in the cutting zone.

KEYWORDS: self-propelled rotary tools; difficult-to-cut materials, hard turning; chip-tool contact length; thermal behavior of SPRT; AISI 4140 Hardened Steel

1. INTRODUCTION

Turning of difficult-to-cut materials plays a significant role in the manufacturing industry and aims to produce high quality machined products while minimizing the production time and cost, however it still poses some challenges to address. In particular, the main issue facing machining of difficult-to-cut materials, such as hardened steel, is excessive wear of cutting tool. Tool wear in machining difficult-to-cut materials occurs due to evaluated temperature generated as a result of the energy consumed to process high strength material materials. Resultant tool wear also results in poor surface finish of machined parts and increases production time and cost due to the stoppage to change inserts [1]. Therefore, a number of research studies have been conducted entailing the development of non-conventional approaches, such as machining with a rotary tool, for machining difficult-to-cut materials.

Using a non-conventional rotary tool has shown high potential when machining hardened materials in terms of improved surface quality and extended tool life [2]. Especially, the application of a rotary tool can be used for various machining processes such as turning, drilling, face milling. Self-propelled rotary tool (SPRT) exemplify a successful implementation of these rotary tool, in which a round insert is attached to the tool holder to add rotational motion to the cutting insert (rotating about its axis) during the turning process as shown in Fig. 1 [3].

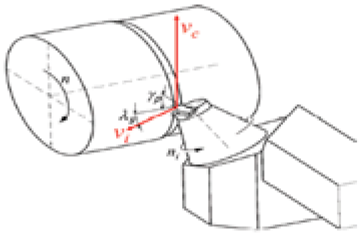

Fig.1 Self-propelled rotary tool (SPRT) [4].

The rotational motion of the round insert is driven by the workpiece revolution with the inclination of the cutting insert in relation to the workpiece axis. The main idea of the rotary insert is to get continuously a fresh cutting edge into the cutting zone to eliminate the effect of generated high temperature and thermal energy, which affects tool wear and surface quality, especially in the case of difficult-to-cut materials [5]. Besides, the benefits of rotary tools on the sustainability of the machining process by compensating the uses of coolant fluids in most cases during the process. Also, it increases the reliability of the turning process and its high productivity by applying larger depths of cut and feed rates without negative impact on working insert.

At the beginning of the 21st century, Kishawy et al. [6, 7] carried out a performance assessment of SPRT and showed that the tool wear was lower than those found in the case of fixed tool (FT) and established an analysis model to identify the heat characterization and temperature of SPRT. The temperature of the cutting tool was found critically affected by the rotational speed of the insert. Several studies have concluded that using SPRT improves the machining performance of hard-to-cut materials [8]. A number of research studies have been conducted to examine the influence of inclination angle and cutting conditions on different process responses when using SPRT in turning operation. Significant effects were found for SPRT on machining performance in terms of power consumption, cutting temperature and chip evacuation as well as surface quality and tool wear. Nevertheless, process parameters and SPRT characteristics were reported to have a significant effect on surface roughness [9]. Furthermore, SPRT can be used to promote changes in machining attributes which plays an important role in machining performance. In particular, and for example, increasing of SPRT tilting angle reduces the friction between the chip and tool face and decreases the chip compression factor due to decreasing in plastic deformation intensity as a result of low temperature and pressure in the cutting zone. However, thermal behavior was found to be affected negatively by the substantial increase in SPRT tilting angle during machining process as increasing tiling angle results in increasing contact length between the tool and workpiece and thus increases the active nose radius [10]. However, the excessive nose radius increases the cutting forces, thus increases generated cutting temperature.

Looking at the aforementioned reviewed literature, a number of research studies examined the performances of SPRT. Nevertheless, to the best of the authors knowledge, the large body of the reported work dedicated to deal with the mechanical essence of SPRT. In this context, this study is concerned with the applicability of SPRT on the machining response of difficult-to-cut material, and aims to explain the influence of tilting angles of SPRT on generated cutting temperature as well as to compare the performance of SPRT with FT in terms of thermal behavior.

2. EXPERIMENTAL WORK

In this section, the detailed experimental setup of the SPRT is described. Characterization criteria are implemented to determine the machining performance in terms of thermal behavior of a cutting tool and organized as follows: Section 2.1 illustrates the structure of SPRT and the selection of cutting insert, Section 2.2 presents the chemical composition and preparation of the material to be machined. Section2.3 reports on the experimental setup. Section 2.4 describes the temperature measurement of cutting tools.

2.1 Structure of SPRT and insert selection

The secret behind the SPRT prototype is the rigidity of the clamping mechanism of all parts of the tool, where the tool consists of four main parts as shown in Fig. 2. Part No. (1) is the rotating insert, while the second part is the insert holding shaft (2) which allows a single degree of freedom in the form of rotary motion and its fitted with the shaft holder (3) through the bearing system. The shaft holder designed with the specific dimension using wire cutting machine to achieve a high degree of mobility with stability guaranteed against cutting forces during rotation of insert shaft. Finally, the fourth part is called shank (4). In this study SANDVIK Coromant carbide (RCMX 120400 S6 P40) inserts are used, Fig. 3 with the recommended range of cutting parameters that will be presented in Section 2.3.

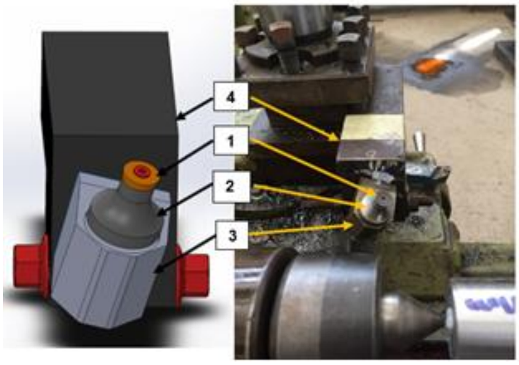

Fig.2 Assembly of the SPRT tool (1. Insert, 2. Shaft, 3. Shaft holder, 4.Shank)

Fig. 3 SANDVIK inserts (RCMX 120400 S6 P40)

2.2 Workpiece material

The stock material used for these machining testsis AISI 4140 hardened alloy steel. The selected material has good mechanical properties, high hardness in the range of 47±1 HRC. appropriate heat treatments were conducted to achieve the required hardness of the AISI 4140 hardened alloy steel. The chemical composition of the AISI 4140 hardened alloy steel is shown in Table 1.

Table 1 Chemical compositions of the AISI4140 Alloy Steel

Element	**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Fe**
Average	**0.383**	**0.752**	**0.382**	**0.0178**	**0.034**	**1.10**	**0.21**	**Balance**

Specimens prepared to be machined were a round bar of 40 mm diameter and 120 mm length. It is worth stating that initial experimental work was carried out on AISI 4140 hardened alloy steel to evaluate the stability of the SPRT, and at the same time to identify the appropriate cutting conditions and their ranges during the screening process.

2.3 Experimental Set-up

The machine used for turning trials was a lathe class162 with a recommended wide range of cutting conditions. All turning operations were conducted under dry conditions without coolant. The tool holder was attached to the tool post, while the developed SPRT rig was used to allow different tilting angles.

2.3.1 Configuration of a cutting tool and workpiece

Adjustment of cutting tool and workpiece were implemented in several steps as shown in Fig. 4 and Fig. 5.

Fig. 4 Multiple Setup for machining processes, Preparation of specimens and install the SPRT and adjust run out using dial indicators

Fig. 5 SPRT Set-up, Install the tool and tool holder and adjust the tool at a machining center for different tilting angles.

2.3.2 Experimental conditions

Initially, Screening operations were carried to establish an effective range of tilting angles as shown in Table 2.

Table 2 Cutting conditions

Factor	**Condition**	**unit**
Specimen	**AISI4140 alloy steel**	**-**
Cutting speed (Vc)	**85**	**[m/min]**
Feed (f)	**0.56**	**[mm/rev]**
Depth of cut (a)	**0.53**	**[mm]**
Tilting angle (i) of SPRT	**25°, 30°, 35°, 40°, 45°**	**[deg.]**

2.4 Temperature measurement

Temperature measurement were performed using an advanced infrared thermal camera with touch screen, high-resolution 384x288 pixel with an IR

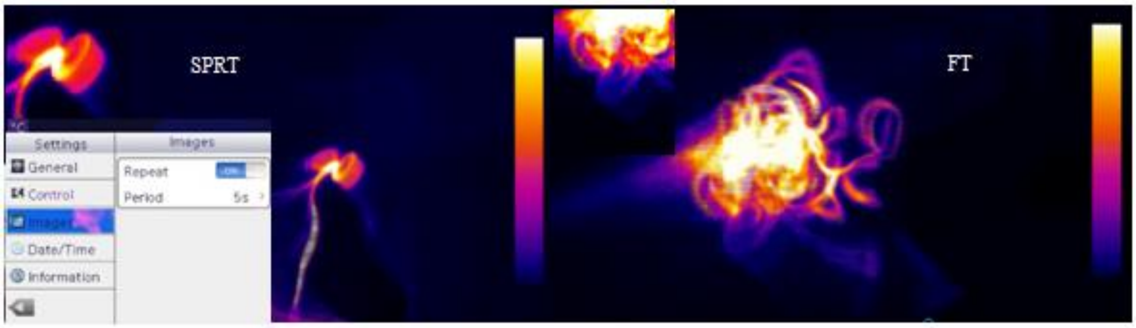

Fig.5 illustrates an experimental work while measuring temperature for both SPRT and FT

sensor. Its settings were adjusted so that a picture was taken every 5 seconds to obtain sufficient data during the measurement process as shown in Fig.5. The camera was calibrated and set to the appropriate position and distance and these procedures were repeated for all trials, whether for SPRT or FT and also in case of changing the tilting angles of SPRT for collecting data to analyze and compare the performance of SPRT and FT, as well as the effect of tilting angle on the thermal behavior of the cutting tool.

3 Results and discussion

3.1 The influence of tilting angle on tool temperature

The temperature distribution of the rotary tools depends on many factors that affect the thermal behavior such as tool diameter, the tilting angle of the tool, the peripheral speed of the tool as well as cutting parameters and properties of tool material and the materials to be machined. It was found that these factors are also affected by each other such as the relationship between tilting angles and the spinning speed of the tool. Tilting angle affects the contact time, contact length of cutting edge, as shown in Fig. 6, as well as the friction and cooling rate of tool were affected. Tilting angle is considered a factor that has special importance in term of tool

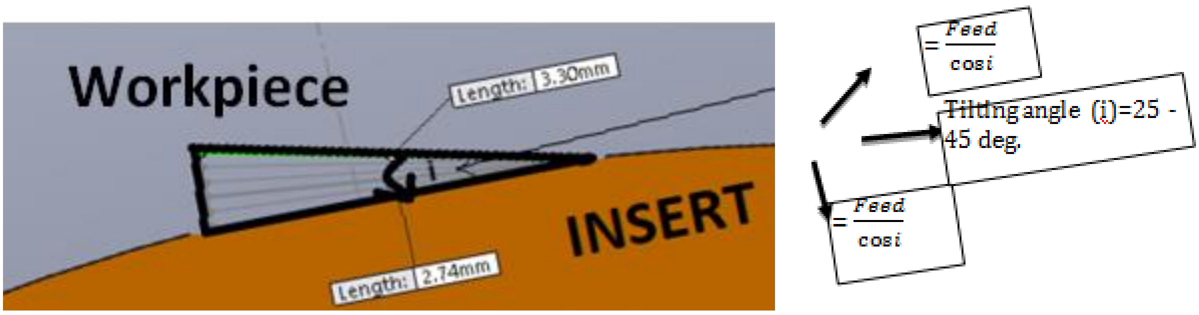

Fig.6 influence of tilting angles on contact length.

Tilting angle is considered a factor that has special importance in term of tool

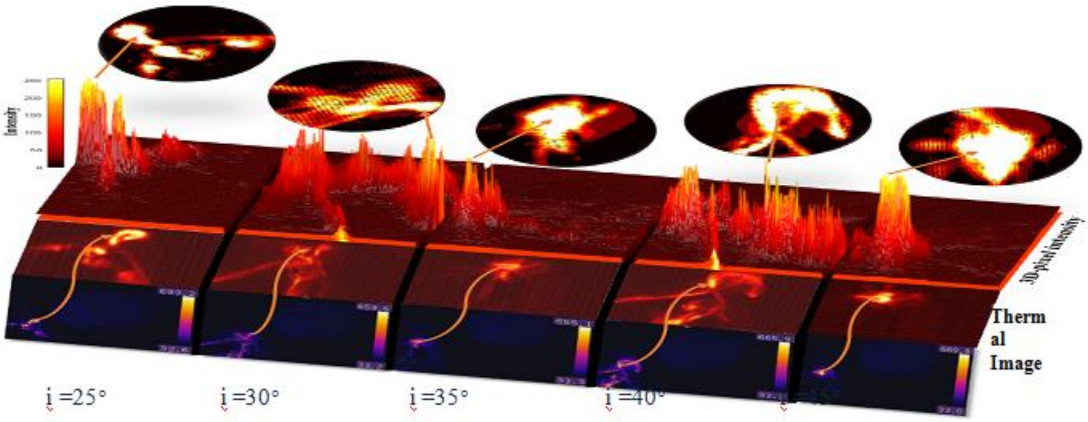

Fig. 7 illustrate the effect of different tilting angles on thermal behavior using SPRT
(Vc = 85 m/min, f = 0.56mm/rev, a = 0.53mm)

temperature when holding cutting parameters at V_c = 85 m/min, f = 0.56mm/rev, a = 0.53mm. Hence, the temperature of cutting tool was affected as shown in Fig. 7. So that the temperature decreases with increasing of tilting angle as a result of increasing the peripheral speed to reach an appropriate value. on the other hand, the opposite effect occurs when the tilting angle increases continuously. therefore, the temperature rises again as a result of increasing the peripheral speed and contact length of the cutting edge of the cutting tool and exceed the critical speed. Also, there are different reasons such as friction conditions and insufficient cooling rate of non-contact /contact area of cutting edge. It is not difficult to see that the closer tilting angle values to 35 deg have lower temperature as shown in Fig.8. At this tilting angle, the spinning speed increases by approximately 26%. Hence, it reduces the temperature of cutting tool by 5.49 % approximately. while further increases of tilting angle increase contact length and spinning speed. Thus, reduced the effective cooling time per one revolution for non-contact/contact portion of the cutting tool.

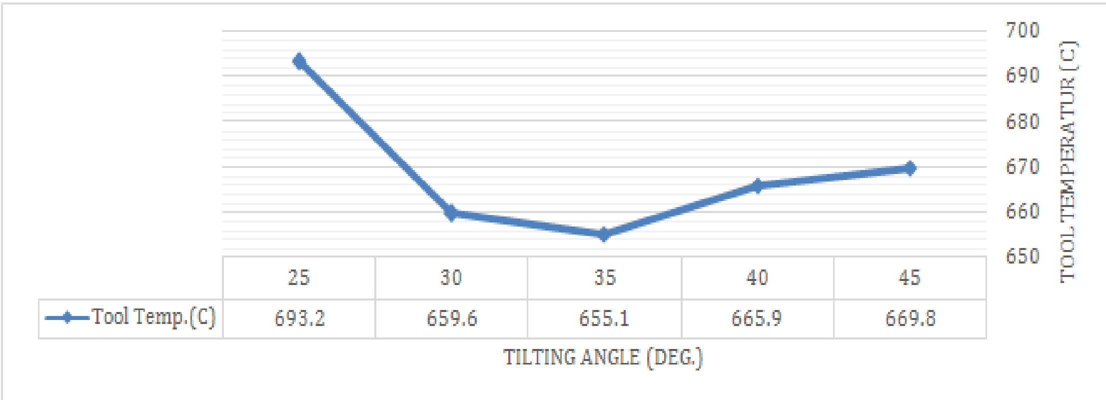

Fig.8 Influence of different tilting angles on thermal behavior using SPRT (Vc = 85 m/min, f = 0.56mm/rev, a = 0.53mm)

3.2 Rotary tools versus Stationary tool

A comparison of tool temperature for both SPRT and FT was made with the assistance of MATLAB software as shown in Fig. 9 and Fig. 10 during machining AISI 4140 alloy steel. SPRT is used to keep the temperature of the cutting tool at a lower level than that in FT because of the SPRT provide a fresh cutting edge continuously into the cutting zone to eliminate the effect of high temperature and thermal energy. In SPRT the cutting portion of cutting edge has ability to change continuously as a result of Spinning action of cutting tool. Therefore, the ambient air passes through the changed portion of cutting edge and absorb the temperature from it before another contact with workpiece. But the cutting potion of cutting edge in fixed tool doesn't able to change which accelerate the amount of heat in the cutting zone. This leads to a significant difference in temperature so that the temperature in the case of SPRT decreases by 200 C approximately than that in the case of FT as shown in Fig.11.

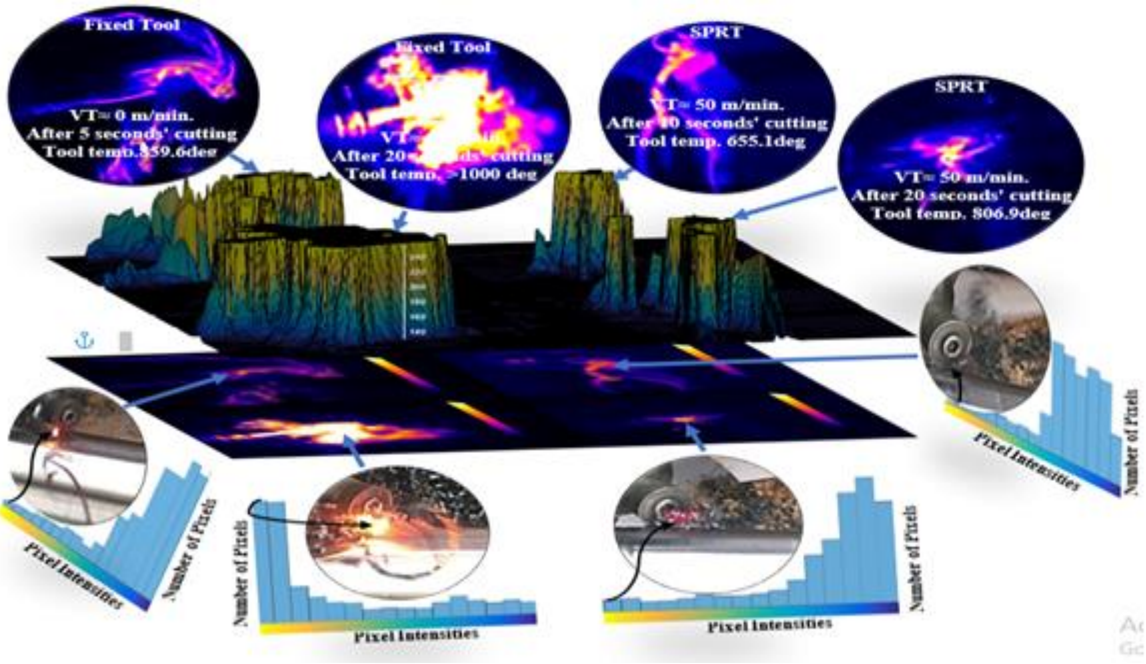

Fig.9 Shows the temperature difference for SPRT and FT at a 10-second and 20-second machining time (Vc = 85 m/min, f = 0.56mm/rev, a = 0.53mm)

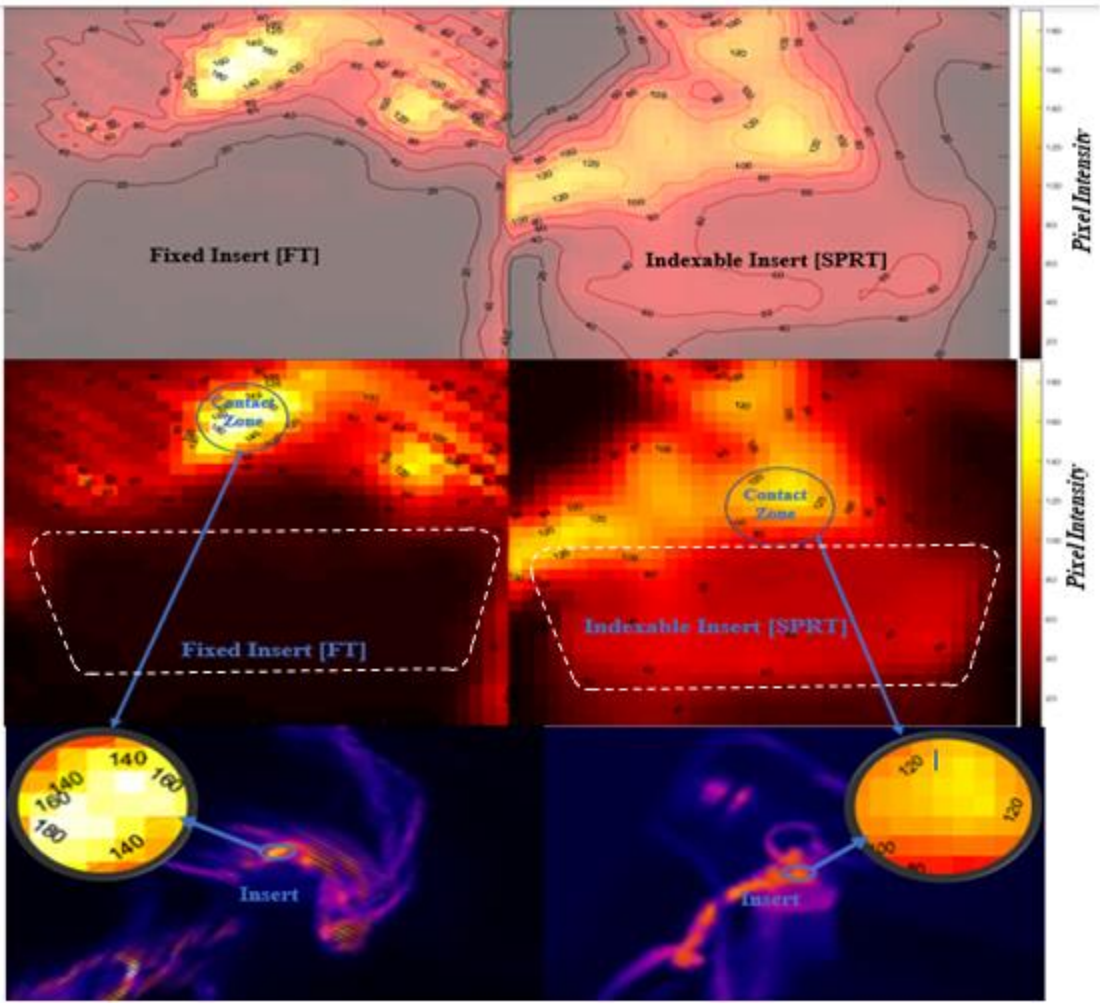

Fig. 10 illustrate temperature distribution over cutting tool for both SPRT and FT

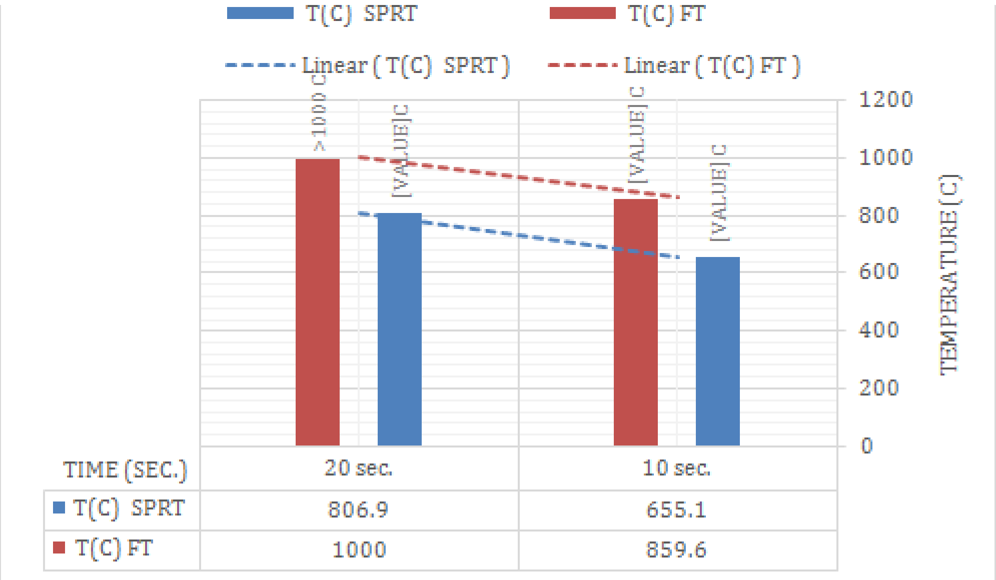

Fig. 11 A comparison of cutting temperatures for both SPRT and FT after machining time of 10sec, and 20 sec. for the same cutting conditions

4. Conclusions

In this paper, an experimental investigation has been carried out using an SPRT to understand the effect of tilting angle on the thermal behaviour of cutting tool, SPRT and FT, during machining AISI4140 alloy steel. The analyses are adopted using MATLAB software. Finally, the following conclusions have been drawn:

- SPRT can be used with a wide range of tilting angles varied between 20^{o}-45^{o}.
- SPRT can be considered as environment friendly due to applicability under dry conditions during the machining of difficult to cut materials.
- Tilting angle has a significant effect particularly to reduce the temperature of cutting tool by 5.49 % approximately for the case of 35 ^{o} when compared with the 25^{o} tilting angle.
- The positive effect of tilting angles on tool-workpiece contact length was observed in this study.
- The temperature of SPRT decreases by 200 °C approximately than that in the case of FT for the same cutting conditions.

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