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# Thermal Field Analysis of Oblique Machining Process with Infrared Image for AA6063-T6

**Osamah F. Abdulateef*** **Lara A.Salman****

**,**Department of Automated Manufacturing Engineering / Al-Khwarizmi College of Engineering/ University of Baghdad*

*E-mail: drosamah@kecbu.uobaghdad.edu.iq

**E-mail: laraa.salman@yahoo.com

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## Abstract

Metal cutting processes still represent the largest class of manufacturing operations. Turning is the most commonly employed material removal process. This research focuses on analysis of the thermal field of the oblique machining process. Finite element method (FEM) software DEFORM 3D V10.2 was used together with experimental work carried out using infrared image equipment, which include both hardware and software simulations. The thermal experiments are conducted with AA6063-T6, using different tool obliquity, cutting speeds and feed rates. The results show that the temperature relatively decreased when tool obliquity increases at different cutting speeds and feed rates, also it is found that the mean tool rake face temperature distribution decreases with increase of tool obliquity. The result also show that the maximum error between the predicted and measured temperatures by IR camera was between 6-27 °C.

***Keywords:*** *Infrared, Deform-3D, tool obliquity, turning.*

## 1. Introduction

Machining is one of the most widely used production techniques in industry for converting preformed blocks of metal into desired shapes with a certain surface quality and dimensional accuracy. These shaping operations are done in forms of metal chips. In the machining processes, material is removed from the surface of the work-part by a cutter and a chip will be formed [1]. During a metal cutting operation, high temperatures are generated because of plastic deformation of workpiece material and friction along the tool/chip interface. Determination of the temperature effect in tool, chip and workpiece is important for process efficiency because the temperatures have a great influence on the rate of tool wear, tool life strength of the workpiece material, mechanics of chip formation and cutting forces [2]. There are two important areas where heat is generated in the contact zone. These zones are the primary and secondary deformation zones. The primary deformation zone generates heat from plastic deformation and softening of the tool material which is caused by high temperatures. This is the zone created by chip formation. The secondary zone generates heat due to frictional sliding and the amount of work done to produce chip deformation [3]. The heat distribution in both zones is due to the depth of cut, feed rates, and cutting speed which is the motion setting on the lathe that determines the rotational speed of the workpiece [4]. One of the most extensively used experimental techniques to measure the temperature in machining is the use of thermocouples. In addition to thermocouples, the infrared (IR) radiation techniques are probably the second most used method for the temperature measurement in machining [5]. In the last two decades, FEM has been most frequently used in metal cutting analysis. Hollander and Englund [6] used thermocouples to verify an electrical-analog analysis for a dry, orthogonal cut of uniform depth at uniform cutting velocity on the edge of a flat workpiece. They used a fine-wire thermocouple to measure the isotherm patterns. O'Sullivan and Cotterell [7] measured the temperature in the turning of aluminum 6082-T6 by using two thermocouples in the workpiece. They indicated that the increasing in cutting speeds will decrease the machined surface temperatures due to the higher metal removal rate. The latter will result more heat being carried away by the chip and thus less heat being conducted into the workpiece. Dewes [8] used Agema Thermovision 900 for temperature measurement in high-speed machining of hardened die steel (SAE H13) (hardness 52HRC). The IR camera has a temperature range (-10 to 2000 °C), the images were obtained at a frequency of 30 Hz. They used this system to find maximum temperatures and not the temperature contours. M'Saoubi and Chandrasekaran [9] used an infrared charge coupled device (IR-CCD) camera to determine the temperature distribution at the cutting edge of the tool. The camera had 510 x 492 pixel array and 40 μs integration time. AFNOR 32CDV12 (HV270) steel was machined with a cermet tool for cutting speeds ranging from 100 m/min to 400 m/min and for feeds ranging from 0.15 mm/rev to 0.3 mm/rev. The results show that the maximum temperature point is located on the rake face at the tool/chip. Bareggi [10] performed FEA for orthogonal metal cutting operation using DEFORM-3D software. An AISI 1020 steel workpiece was modeled and insert tungsten carbide tool was used. The using cutting conditions are cutting speed 270 m/min, feed rate 0.06 mm/rev and depth of cut 0.5 mm.

Investigations indicated that there is a reduction in temperature when the high velocity air jet is applied during the metal cutting. Jaharah [11] predicted 3D-FE modeling using DEFORM software on the finish hard turning. The experiments were performed using AISI 1045 with the effect of various machining parameters of cutting speed 100m/min to 300m/min and feed rates (0.15 mm/rev to 0.35 mm/rev). The results show that the effective cutting temperature at the cutting edge were between 605°C and 2080°C.

## 2. Finite Element Analysis (FEA)

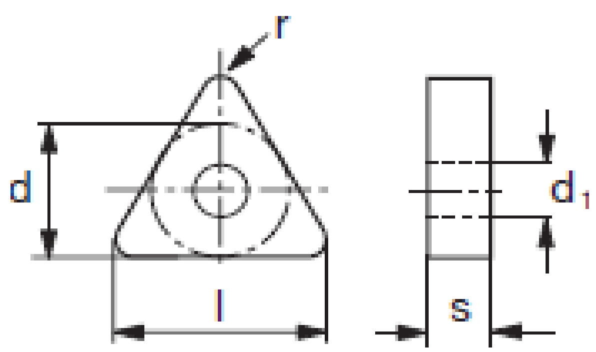
Experimental studies in metal cutting are expensive and their results are valid only for the experimental conditions used and depend greatly on the accuracy of the calibration of the experimental equipment and apparatus used. An alternative approach is the numerical methods. Several numerical methods have been used in metal cutting studies, for instance, the finite difference method (FDM), FEM, the boundary element method (BEM) etc. Amongst the numerical methods, FEM is the most frequently used in metal cutting studies. The choice of the FE software for metal cutting analysis is very important for the quality of results. This is because different FE packages have different capabilities and solver techniques [2]. Because the oblique machining process modeling more complicated than orthogonal cutting and need three-dimensional analysis to be performed to study oblique cutting. In this research DEFORM-3D FEM will be used to simulate the temperature distribution.

## 3. Modelling Procedure

In this analysis the cutting tool was assumed to be a rigid body and the tool material selected was uncoated tungsten carbide with 0.8 nose radius and about 5° rake angle. The FE mesh of the tool was modeled using 6913 nodes and 29939 elements. The automatic mesh generator was applied with a higher mesh density near the cutting zone of the tool to obtain more accurate temperature distribution results. The dimensions of the insert are shown in table 1. The mesh design is shown in Fig. 1.

**Table 1,**
**The dimension of insert tungsten carbide.**

| l (mm) | d (mm) | s (mm) | d1(mm) | r (mm) |
|---|---|---|---|---|
| 17 | 12.7 | 4.7 | 3.8 | 0.8 |



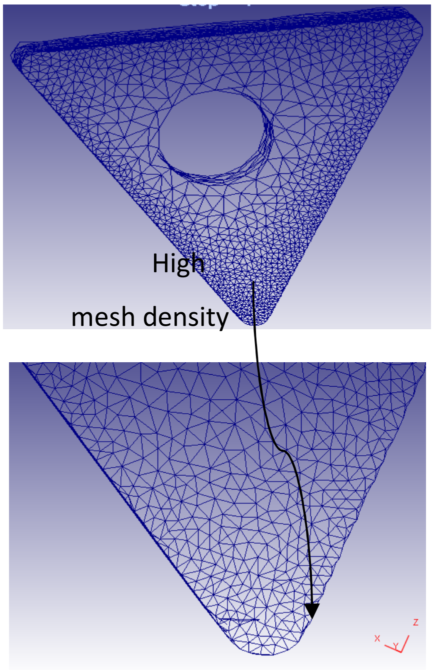



**Fig. 1. Mesh design of the tool.**

The tool was subjected to motion in (+y) directional and constrained against movements in x and z directions. The workpiece material AA6063-T6 was used and assumed to be a plastic material. The total number of elements was 5000 to 80000 depending upon workpiece size. The automatic mesh generator was applied with a higher mesh density near the cutting zone of the workpiece in order to reduce calculation time and obtain more accurate results, see Fig. 2.

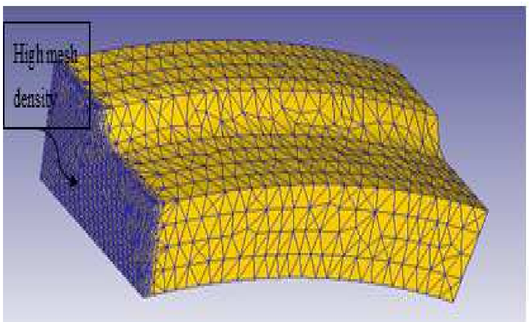
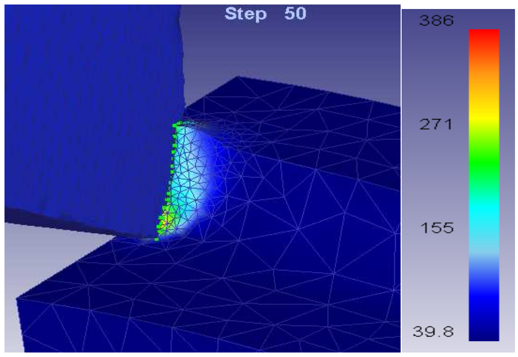
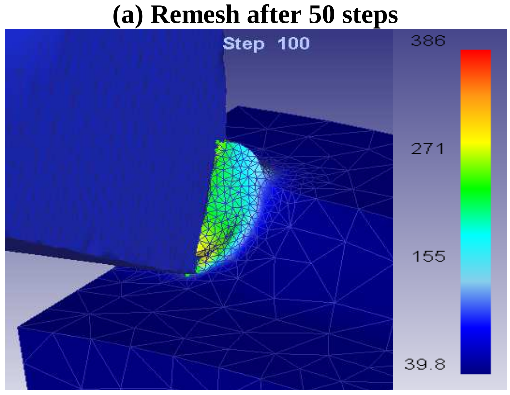



**Fig. 2. Mesh design of the workpiece.**

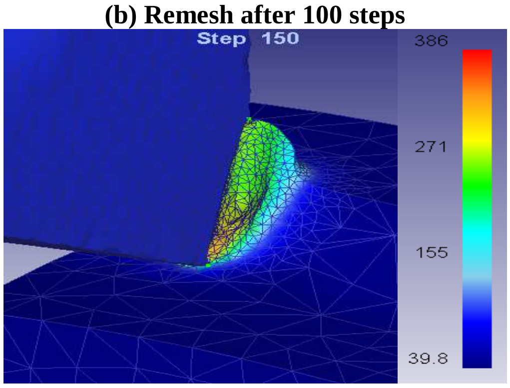
Heat exchange was applied to the surface of the tool and workpiece. A plastic and thermal property of workpiece was given to the software for heat transfer calculation. The next step after modeling the metal cutting components is assembling them due to the cutting conditions. The contact between the workpiece and the tool is another important step to define. The tool is selected as the master object because it was defined as a rigid object. The workpiece is defined as slave object. Then, the friction coefficient and the interface heat transfer coefficient are defined. Fig. 3 (a-d) shows the remeshing generation procedure at cutting zone at different steps.



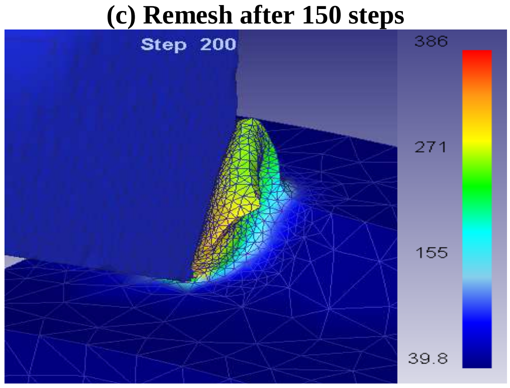

**(a) Remesh after 50 steps**




**(b) Remesh after 100 steps**




**(c) Remesh after 150 steps**




**(d) Remesh after 200 steps**

**Fig. 3. Remeshing procedure at cutting zone.**

## 4. Experimental Procedure

In order to validate the tool temperature prediction model in the oblique machining process, the temperature measurement was made with an infrared thermal imaging camera. The specific temperature measurement device used was a FLIR camera model T335 see Fig.4. The Flir T335 offers an outstanding solution for professional thermographers who require a high resolution camera for conducting electrical and mechanical inspections. FLIR T335 is a small and light-weight infrared camera with excellent image quality. The specification of the camera is as follows; it has an array size of 320×240 pixels and a target image temperature range between –20°C to +120°C, 0°C to +350°C , +200°C to +1200°C. The spectral responsivity of the camera is 7.5–13 μm and the target emissivity varying from 0.01 to 1.0 or selected from materials list. Image frequency is 30 HZ and image zoom is (4:1) [12]. The camera was connected via USB cable to a laptop that ran FLIR Quick Report software.


**Fig. 4. Thermal image camera FLIR T335 [12].**

In this experimental work all the turning tests were performed using lathe machining (WILTON lathe). The workpiece material AA6063-T6 was used. The workpiece have 40 mm diameter and about 225 mm length. The tool used in the oblique machining process was insert tungsten carbide with about 0.8 nose radius and about the 5° rake angle. No cooling was involved during the cutting process. The field of view for the camera had to be consistent. Therefore, the camera has to be attached to the tool carriage using a stand, see Fig. 5. In the experiments, the most interesting area to be captured was the rake face. Therefore, the IR camera lens is focused on this region; starting from the tool tip.

**Fig. 5. Set up the camera in the tool carriage.**

A number of different experiments are performed with the infrared camera set up for oblique cutting of the workpiece material, because it is necessary to find images which are free from any flying chips or small metallic particles. In order to make an accurate measurement in the experimental work by IR camera, the emissivity for each material was selected from the materials list, and in order to validate the temperature model simulations and experiments with the IR camera are performed at conditions as shown in table 1. The properties of the workpiece material (AA6063-T6) are shown in table 2.

**Table 1,**
**The cutting condition for thermal simulation and experimental validation**

| Workpiece material | Tool obliquity (ϴ) (deg) | Cutting speed (VC) | | Feed rate (f) (mm/sec) | Depth of cut (DOC) (mm) |
|---|---|---|---|---|---|
| | | (rpm) | (m/mi) | | |
| AA6063-T6 | 10,20,30 | 950,1350 | 119.32,170 | 3.2, 3.6, 4, 4.4, 5.3, 6.5 | 1 |

**Table 2,**
**Chemical composition of workpiece material AA6063-T6 AL alloy**

| Workpiece materail | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| **AA6063-T6** | 0.45 | 0.25 | 0.1 | 0.05 | 0.6 | 0.08 | 0.09 | 0.02 |

## 5. Results and Discussion

For the criterion of the maximum tool rake face temperature, the results of every experiment are analyzed separately, and the results are given in Fig.6 to Fig.11 for AA6063-T6 AL alloy, respectively. Considering the test conditions for the oblique cutting of Al, it is found that for all tested cutting conditions, the predicted cutting temperature shows a similar trend as the measured temperature when it is analyzed. Also it is found that the predicted and measured maximum tool rake face temperatures are located near to the tool tip but not on the tool tip. The highest tool temperatures were predicted in the rake face at the primary cutting edge, this is due to the additional heat generated by the chip sliding mechanism on the rake face.

It is clear that the maximum tool-chip interface temperature increases with increasing cutting velocity at angles of 10°, 20° and 30° tool obliquity. When high value of cutting speed used in the cutting process, this means increased the power to remove more material in a shorter time. The power consumed in metal cutting was largely converted into heat, which leads to increase the heat generated near the cutting edge of the tool, so high value of temperature obtained. These results are agreed with those reported in earlier works in [5, 13 and 15]. Another fact that can be seen from the results of these experiments is that the maximum tool-chip interface temperature increases with increasing federate. The maximum simulated and measured rake face temperature error are shown in table 3. It was clear that from the Figure below for Al at different tool obliquity, when the feed rate increased high temperature is generated due to cut large pieces from the metal in one revolution, which transmitted as a heat between tool and workpiece. Also from the predicted and measured temperature distribution for Al at angles of 10°, 20° and 30° tool obliquity, it is found that the tool temperature relatively decrease when tool obliquity increase at different feed rates.

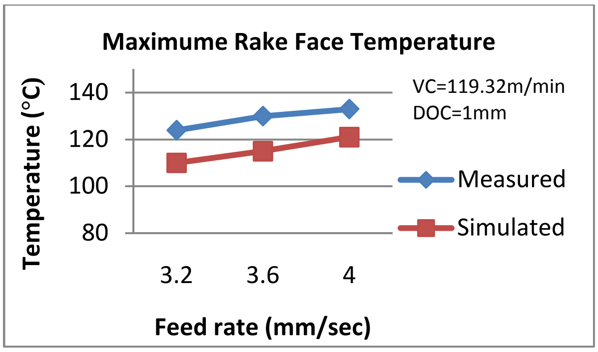



**Fig. 6. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 10° tool obliquity, 5° rake angle tool.**

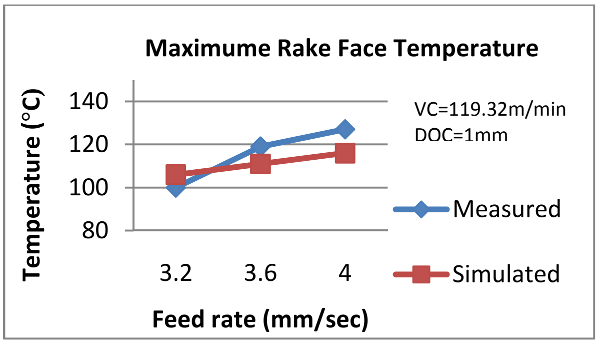



**Fig. 7. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 20° tool obliquity, 5° rake angle tool.**

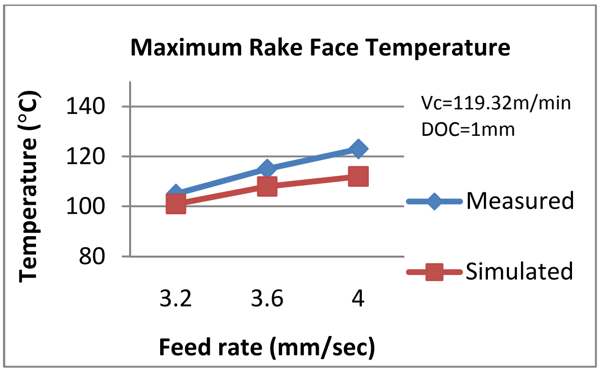



**Fig. 8. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 30° tool obliquity, 5° rake angle tool.**

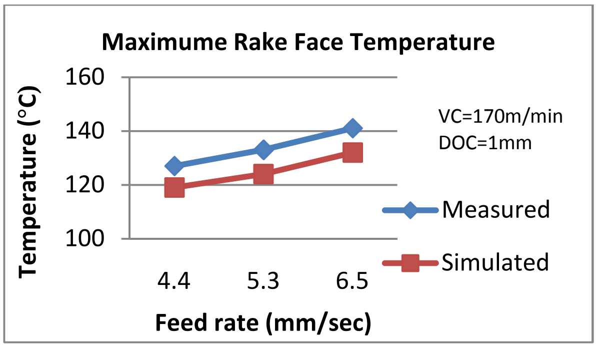



**Fig. 9. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 10° tool obliquity, 5° rake angle tool.**

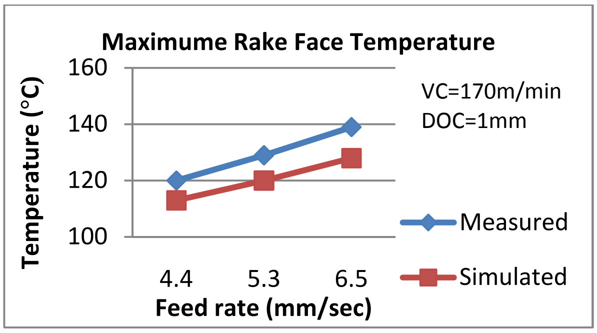



**Fig. 10. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 20° tool obliquity, 5° rake angle tool.**

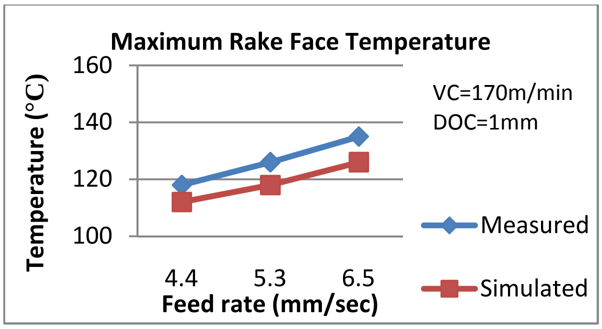



**Fig. 11. The simulated and the measured maximum rake face temperatures of AA6063-T6, machined with a 30° tool obliquity, 5° rake angle tool.**

The analysis of the mean rake face temperature and the rake face temperature distribution were carried out for AA6063-T6 AL alloy, machined with a tungsten carbide tool having a rake angle of 5°, with a cutting velocity of 119.32 m/min and a feed rate of 4mm/sec, and with a tool obliquity of (10°, 20°, and 30°). The tool measured temperature distribution with infrared camera and the contour plot that obtained by transferring the thermal image from FLIR Quick Report to the Matlab software are shown in Fig.12.

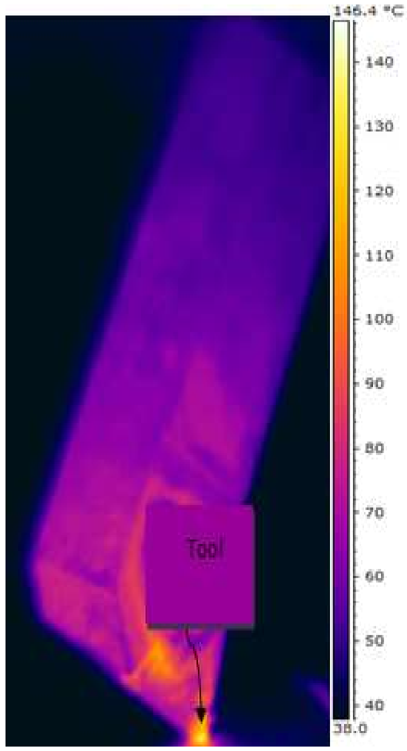



**Fig. 12 (a). Tool measured temperature Distribution with IR camera AA6063-T6 (in C°), VC = 119.32 m/min, f=4 mm/sec,DOC= 1 mm, tool obliquity=10°.**

**Table 3,**
**Maximum rake face temperature error.**

| materials | Cuttin g speed (m/min) | Feed rate (mm/sec) | Tool obliquity | Measur (°C) | Simulat (°C) | Error % |
|---|---|---|---|---|---|---|
| AA6063-T6 | 119.3 | 4 | 10 | 133 | 122 | 11 |
| | | | 20 | 127 | 116 | 11 |
| | | | 30 | 122 | 111 | 11 |
| AA6063-T6 | 170 | 6.5 | 10 | 141 | 132 | 9 |
| | | | 20 | 139 | 128 | 11 |
| | | | 30 | 135 | 126 | 9 |

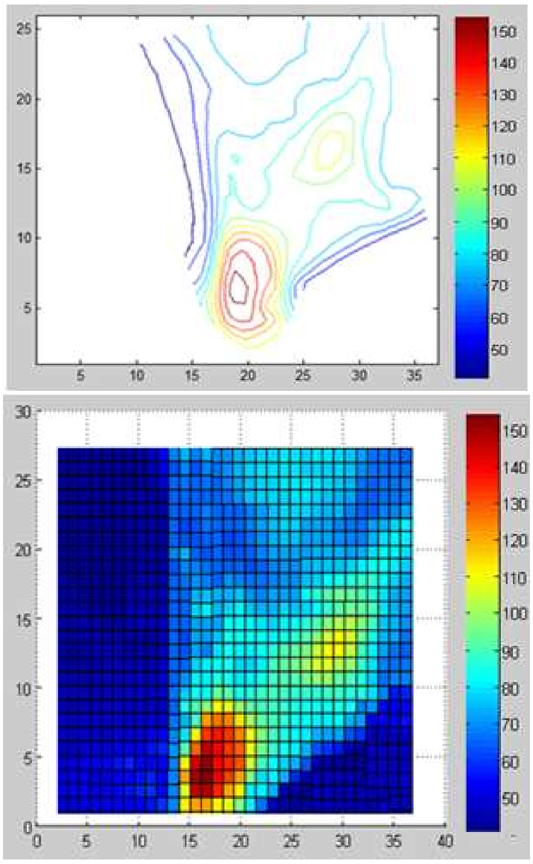
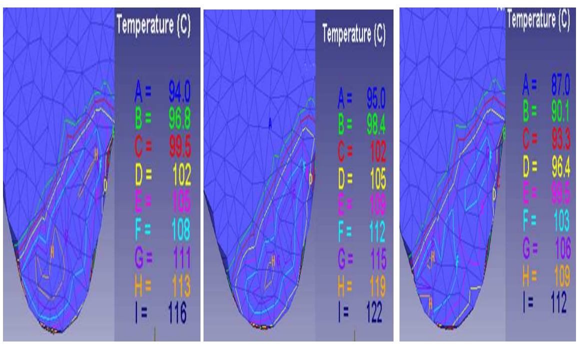


**Fig. 12(b). Tool measured temperature distribution AA6063-T6 (in C°), VC = 119.32 m/min, f=4 mm/sec, DOC= 1 mm, tool obliquity=10°.**

The predicted tool temperature distribution of AA6063-T6 with 10°, 20° and 30° tool obliquity are shown in Fig. 13.



(a) (b) (c)

**Fig. 13. Tool predicted temperature distribution of AA6063-T6 (in C°), VC = 119.32m/min, f = 4 mm/sec, DOC = 1 mm, (a) 10° tool obliquity (b) 20° tool obliquity (c) 30° tool obliquity.**

It can be easily seen from the results that the predicted and measured maximum tool temperatures are located near to the tool tip but not on the tool tip. Also, as can be seen from the results with different tool obliquity the mean tool rake face temperature of aluminum is found a decrease with increasing tool obliquity [14]. The validation of the rake face temperature distribution and the mean rake face temperature is given in Fig. 14 to Fig. 16. As can be seen in the results the mean rake face temperature has reached to 115 °C (simulated) and 127 °C (measured) for AL at 10° tool obliquity, as shown in Fig.14, while at 20° tool obliquity, the mean tool rake face temperature was found to decrease to 106°C (simulated) and 114°C (measured), as shown in Fig 15, and at 30° tool obliquity, the mean rake face temperature has decreased to 101°C (simulated) and 109°C (measured) as shown in Fig. 16.

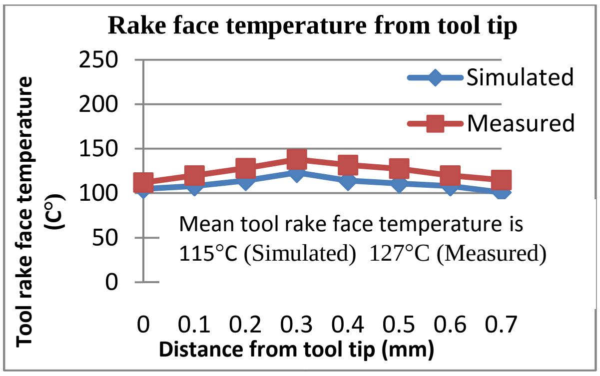



**Fig. 14. The simulated and the measured rake face temperature distribution of AA6063-T6 from the tool tip, with VC=119.32 m/min, tool obliquity =10°, feed rate =4mm/sec.**

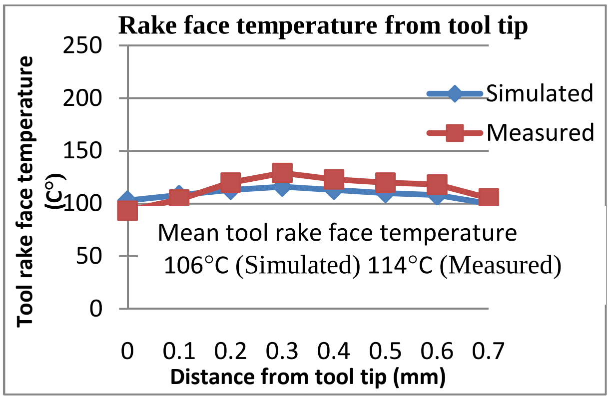



**Fig. 15. The simulated and the measured rake face temperature distribution of AA6063-T6 from the tool tip, with VC=119.32 m/min, tool obliquity =20°, feed rate =4mm/sec.**

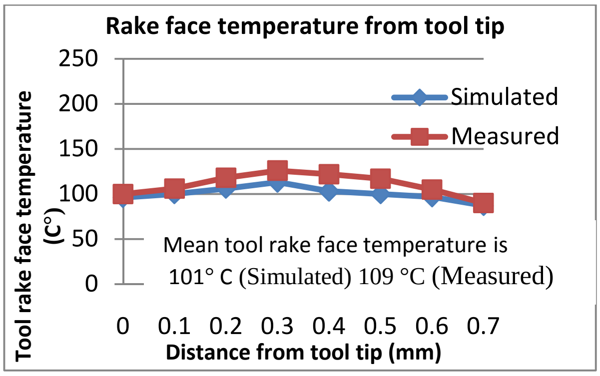



**Fig. 16. The simulated and the measured rake face temperature distribution of AA6063-T6 from the tool tip, with VC=119.32 m/min, tool obliquity =30°, feed rate =4mm/sec.**

The variation of mean rake face temperature with the tool obliquity of AA6063-T6 is shown in Fig.17. As can be seen from these results the decrease of the mean tool rake face temperature with increased tool obliquity has led to enhancement the tool wear and tool life during the machining process.

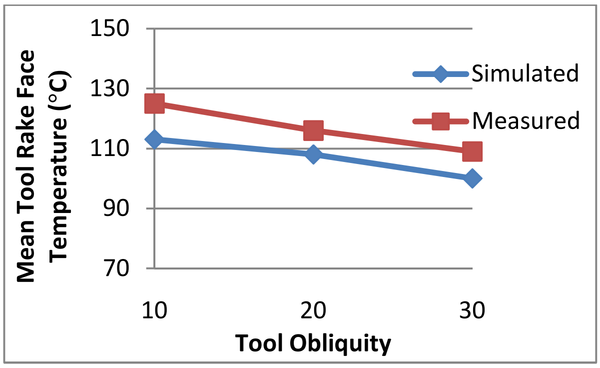



**Fig. 17. Variation of mean rake face temperature with the tool obliquity of AA6063-T6 at VC= 119.32m/min, feed rate=4mm/sec, DOC=1mm.**

## 6. Conclusions

1. The Infrared imaging is found convenient when determining temperature in the cutting zone due to its fast response and its ability to have no effects on temperature during the cutting process. This so because there is no physical contact.
2. The maximum tool temperature distribution for AL is found increases with increasing cutting velocity and feed rate.
3. The predicted and measured maximum tool temperatures are located near the tool tip not on the tool tip.
4. The maximum tool temperature relatively decreased when tool obliquity increase at different cutting speeds and feed rates.
5. The maximum predicted and measured tool temperatures are located near the tool tip not on the tool tip.
6. The mean tool rake face temperature distribution decreases with the increase of the tool obliquity of aluminum which leads to enhancement the tool wear and tool life during the machining process.
7. The result also show that the maximum error between the predicted and measured temperatures by IR camera was between 6-27%.

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[16] Specialized institute for engineering industries.

# تحليل المجال الحراري لعمليه التشغيل المائله

**أسامه فاضل عبد اللطيف* لاره عبد الكريم سلمان****

*قسم هندسه التصنيع المؤتمت / كليه الهندسه الخوارزمي / جامعه بغداد *،**

* البريد الالكتروني : drosamah@kecbu.uobaghdad.edu.iq

** البريد الالكتروني: Laraa.salman@yahoo.com

**الخلاصة**

أن اغلب العمليات التصنيعية والتشغيلية تنجز باستخدام مكائن التشغيل المختلفة،حيث تمرالمشغولات بسلسلة من العمليات التشغيليه المختلفة ابتدأ من المادة الاوليه وصولا الى المنتج النهائي، وتعتبر الخراطه الاكثر استخداما في عمليات قطع المعادن، هذا البحث يركز على تحليل التوزيع الحراري خلال عمليات القطع المائل بأستخدام طريقه العناصر المحدده (FEM) وتطبيقها في برنامج DEFORM 3D V10.2 . تم استخدام ماده الالمنيوم AA6063-T6 بظروف تشغيل متعدده (سرع قطع، تغذيه، ميلان الاداه) .اظهرت نتائج القياسات الحراريه بالاشعه تحت الحمراء ذات الدقه العاليه بعد مقارنتها مع نتائج طريقه العناصر المحدده (FEM) انخفاض متوسط درجات الحراره عند وجه جرف الاداه عند زياده ميل الاداه عند سرعه قطع وتغذيه مختلفه،وكذلك اظهرت النتائج اعلى نسبه خطاء بين درجه الحراره المتوقعه والمقاسه بالكاميرا الحراريه يتراوح بين 6-27 °C.