Experimental Investigation of Thermally Enhanced Machining of Difficult-To-Machine Material Ti-6Al-4V

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Abstract— This work explores thermally enhanced turning process on lathe to improve the machining capabilities of conventional turning process on lathe by heating the work by an external heat source. The present work describes an experimental study of thermally enhanced machining (TEM) by adding an oxy LPG gas cutting setup as an external heat source to the machine setup which heats the work locally and temperature is measured by non-contact infrared thermometer. The experimental data of cutting forces at critical temperatures of difficult-to-machine alloy Titanium (Ti6Al4V) and with full factorial design of experiment ANOVA is presented here. Due to TEM, an increase in cutting tool life, reduction in cutting forces are observed.

Key words: thermally enhanced machining, Ti6Al4V, hot turning on lathe, reduction of cutting forces, tool life improvement

I. INTRODUCTION

Lathe machine and its applications had been commercialized since long. Since then, significant advances have been made in lathe in the form of hardware and software integration, CNC lathe along with newer applications in drilling, turning, taper turning, threading, etc. A wide range of materials is shaped for different applications with this process. The demand of higher strength and heat resistant material is increasing particularly in aerospace industries. However, these materials are often difficult to machine due to their physical and mechanical properties such as high strength and low thermal conductivity, which requires very high cutting energy and makes the cutting forces and cutting temperature very high, and even leads to a short tool life.

The mechanism behind the material removal in conventional Lathe is cutting by the cutting tool. If the machining is carried out at high temperatures, plastic deformation of the material occurs at cutting zone, which leads to increase cutting tool life and reduction of cutting forces. As flow stress and strain hardening rate of materials normally decrease with increase in temperature due to thermal softening (shown in Fig. 1 as the dependence of strength on temperature), this opens an avenue of thermally enhanced machining (TEM) for Difficult-to-machine materials. TEM may use an external heat source to heat and soften the workpiece. As a result, the yield strength, hardness and strain hardening of the workpiece reduces and deformation behavior of the hard-to-machine materials changes to allow the plastic deformation. This enables the difficult-to-machine materials to be machined easily along with low cutting forces, which leads to increase in cutting tool life.

II. LITERATURE REVIEW

Sun et al. (2010) [1] studied the benefits of thermally enhanced machining by focusing on laser and plasma assistance to machine ceramics, metals and metal matrix composites. They also made an attempt to integrate the external heat source with cutting tools.

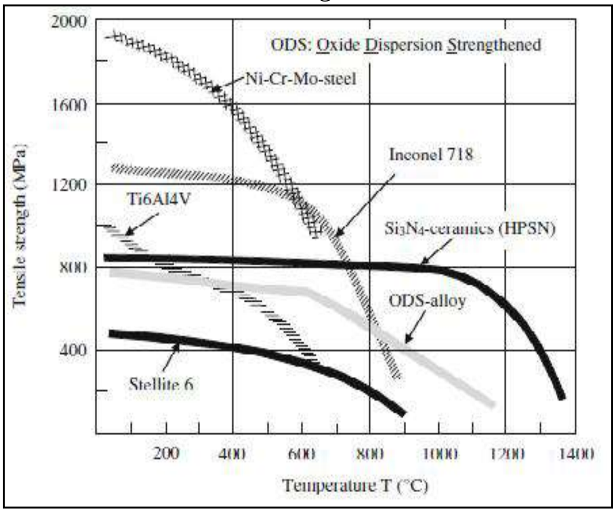

Fig. 1: Effect of Temperature On the Ultimate Tensile Strength For Various Hard-To-Machine Materials (Sun Et Al., 2010).

K. Venkatesan et al(2014) [2]. Studied the benefits of thermally enhanced machining by focusing on Nd: YAG laser assistance to titanium alloys, nickel alloys, ceramics while turning on lathe.

Satyanarayana et a l (2012) [3] performed online tools wear monitoring by cutting forces while turning Ti6Al4V. relations between cutting speed, cutting forces and tool wear are observed.

Hossain et al (2008) [4]. Preheated Ti6Al4V workpiece while end milling process to reduce cutting forces and vibrations of the machine and improved the tool life.

Divyansh Patel et al (2015) [5]. Performed TEM on Ti6Al4V while Abrasive water jet machining to reduce machining time and improve surface finish of the material.

III. EXPERIMENTAL SETUP

Experiments are performed on lathe machine manufactured by panther industries. Lathe tool dynamometer of capacity 500 kg in each direction is attached to the lathe to measure cutting forces in X, Y and Z directions.

Fig. 2: Lathe tool dynamometer

Oxy-LPG gas cutter is used to heat the workpiece up to a critical temperature where the material loses its strength

Fig. 3: Oxy- LPG Gas Cutter

The temperature of the cutting zone is controlled with the help of a infrared thermometer. Non-touch infrared thermometer works on the principle of infrared thermal camera, which detects the temperature with respect to emissivity of the material and temperature range.

Fig. 4: Infrared Thermometer

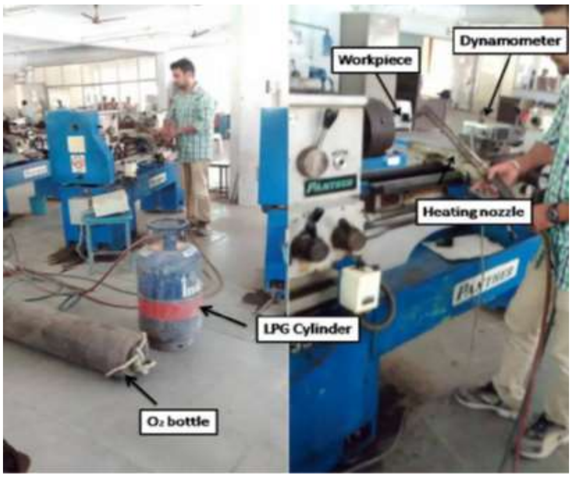

Fig. 5: Experimental setup

A. *Workpiece Material:*

Cylindrical rod of dimension 250X50 mm Titanium alloy Ti6Al4V Grade 5 is used as workpiece material.

Chemical composition of Ti6Al4V				
Aluminium	Vanadium	Iron	Oxygen	titanium
6%	4%	0.25%(max)	0.2%(max)	Remainder

Mechanical Properties of Ti6Al4V	
Density(gm/cc)	4.42
Hardness, Rockwell(HRc)	36
Tensile strength(MPa)	950
Thermal Conductivity(W/m˚C)	6.77

B. *Cutting Tool:*

Fig. 6: Carbide inserted cutting tool

C. *Carbide Insert Details:*

Approach angle	95˚
Orthogonal Rake angle	-6˚
Nose radius	0.4

D. *Tool Holder Details:*

Model: PCLNL2020K12	
Lead angle	95˚
Length(mm)	125
Qualified width(mm)	25
Shank Height(mm)	20
Shank Width(mm)	20

IV. PROCESS PARAMETERS

The process parameters that can influence thermally enhanced machining are:

1) Cutting speed(m/min): Cutting forces are decrease with increase in cutting speed till certain speed limit. After that it will increase for the Ti6Al4V material.
2) Feed rate(mm/rev): cutting forces increase with increase in feed rate.
3) Temperature(˚C): High temperature is provided at three different levels in this experiment to study its effect on cutting forces.

Depth of cut(mm) is kept constant 0.8mm during all experiments.

The experimental study aims to prove that the cutting forces and can be decrease in lathe turning with thermally assisted machining. For TEM it is observed that cutting forces are affected to a great extent by applying external heat. In this work, temperature is considered as a variable parameter as the effect of temperature on cutting forces and MRR is significant.

Ti6Al4V	
Temperature ˚C	Tensile strength MPa
100	1000
400	730
600	400

Table 1: Tensile properties at elevated temperatures (Sun et al., 2010).

Titanium and its alloys (Ti6Al4V) are in demand by the aerospace industry due to their superior properties like excellent strength-to-weight ratio, strong corrosion resistance and ability to retain high strength at high temperature. The tensile properties of Ti6Al4V alloy at elevated temperature are listed in table 1.

V. EXPERIMENTAL PROCEDURE

The procedural steps are as follows:

1) Preparation of specimen:

Cylindrical solid rod of Ti6Al4V alloy of dimensions 250mm length and 50mm diameter is used. Rod is divided in 5 segments each of 50mm length. First is used to hold the workpiece in lathe chuck. On remaining 4 segments 27 experiments are performed of 50mm length.

2) Preparation of Machining setup:

Workpiece is mounted between the chuck and tailstock centre. Cutting tool is mounted to the tool post. Oxygen LPG gas cutter is handled by skilled operator. Dynamometer is attached to the tool post in which cutting tool is mounted. Infrared non touch temperature gun is used to measure temperature.

Parameters	Level 1	Level 2	Level 3
Cutting speed (m/min)	23	45	60
Feed(mm/rev)	0.05	0.072	0.1
Temperature(˚C)	30	400	600
Depth of cut (mm)	0.8	0.8	0.8

Table 2: List of variable parameters.

3) Parameter setting:

– Cutting speed & Feed:

Cutting speed and Feed is varied by changing gearbox lever as specifications given on the lathe machine.

– Temperature:

In TEM, temperature is an external input parameter. The specimen is heated with the help of oxygen LPG gas torch to a critical temperature where tensile strength of the material decreases. The temperature is controlled with the help of non-touch infrared thermometer.

– Machining:

Workpiece is mounted on lathe machine and facing is performed. After that center is marked on the face with the help of center drill and workpiece is mounted between chuck and tailstock center. First finishing turning is performed to remove irregularities and dust from the surface. With different Speed. Feed, and temperature turning is performed on each 50mm segment.

– Cutting force measurement:

Cutting forces are measured for all 27 experiments with the help of lathe tool dynamometer. Cutting time for each experiment is measured by stopwatch.

Experiments are designed using Design Expert 10, a statistical tool so as to find the sequence of experiments and possible combinations of input parameters. observe the effect of significant factors at 95% confidence level, the results of the response parameters are presented through graphs. Experiments are designed for three levels and three factors i.e., 3^3 numbers of experiments are performed. Experimental setup is shown in fig 5.

VI. RESULTS AND DISCUSSIONS

DIV	RUN	Cutting Speed (m/min)	Feed (mm/rev)	Temperature (˚C)	Axial force Fx (N)	Radial force Fy (N)	Tangential Force Fz (N)	MRR mm^3 /sec
19	1	23	0.05	600	77.91	70.15	163.84	17.4527
26	2	45	0.1	600	89.56	82.2	173.97	63.9827
25	3	23	0.1	600	98.36	91.63	181.12	32.9741
17	4	45	0.1	400	95.76	88.7	178.31	63.8176
13	5	23	0.072	400	96.33	86.74	179.74	26.5520
9	6	60	0.1	30	104.85	95.2	187.32	85.0784
23	7	45	0.072	600	80.48	73.92	165.86	53.6316
12	8	60	0.05	400	81.75	74.15	160.43	46.1529
24	9	60	0.072	600	78.26	70.12	161.18	69.5383
14	10	45	0.072	400	87.25	78.37	171.39	53.5294
4	11	23	0.072	30	112.35	103.76	193.67	26.5008
18	12	60	0.1	400	89.82	82.75	171.96	85.6916
3	13	60	0.05	30	90.28	84.92	175.66	45.9711

10	14	23	0.05	400	82.44	75.27	167.96	17.4414
21	15	60	0.05	600	76.16	68.74	155.62	46.2185
20	16	45	0.05	600	73.88	65.91	158.97	34.6134
7	17	23	0.1	30	119.99	108.04	199.84	32.8707
11	18	45	0.05	400	79.92	71.38	164.98	34.5689
16	19	23	0.1	400	104.42	97.52	185.32	32.9372
27	20	60	0.1	600	83.36	76.84	167.3	85.9179
2	21	45	0.05	30	98.31	88.51	182.26	34.4687
6	22	60	0.072	30	97.25	90.62	181.32	68.9874
15	23	60	0.072	400	84.75	76.92	165.44	69.3978
8	24	45	0.1	30	112.34	107.18	193.65	63.4769
5	25	45	0.072	30	105.11	97.22	187.95	53.3079
22	26	23	0.072	600	89.67	82.25	172.45	26.5726
1	27	23	0.05	30	104.27	96.38	186.58	17.4168

Table 3: Result Table

The recorded output responses are fen into Design Expert 10 to Analyze combine effects of Cutting speed, feed and temperature on the Cutting forces. Graphs are generated in Design expert 10.

A. Cutting Forces Reduction:

As per experimental results cutting forces decrease and MRR increase with increase in external temperature for the same value of cutting speed and feed. Following are different charts represents the effects of variable parameters on cutting forces.

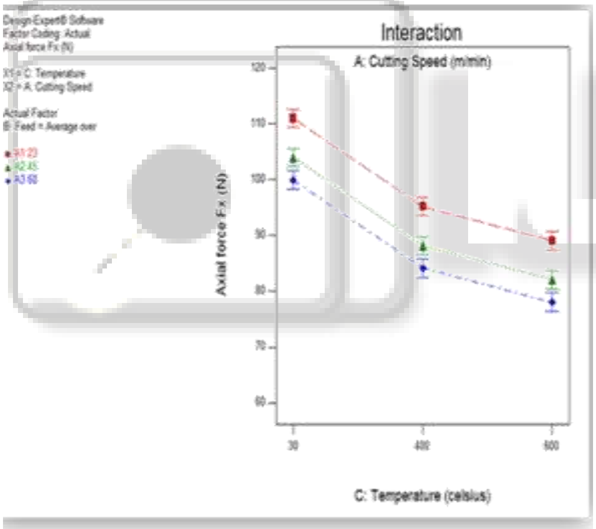

Fig. 7: Temp(˚C) v/s Axial force Fx (N)

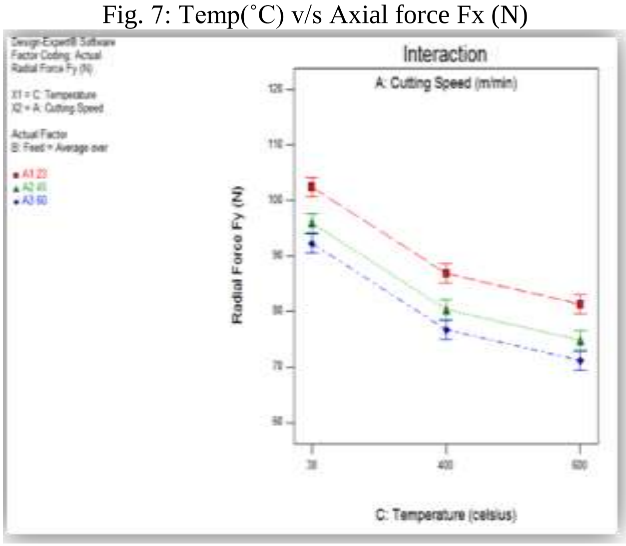

Fig. 8: Temp(˚C) v/s Radial force Fy (N)

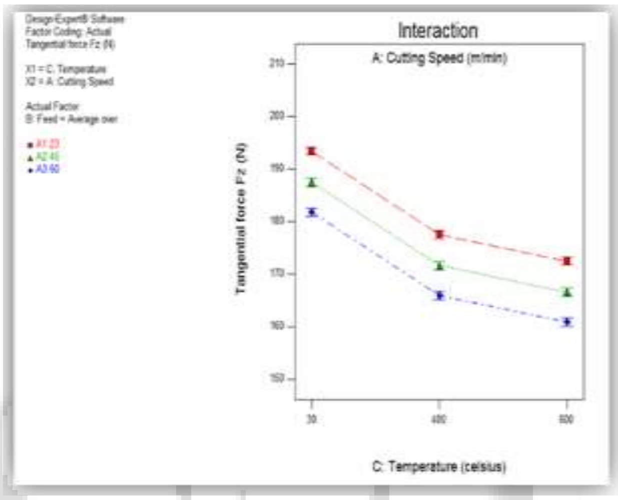

Fig. 9: Temp(˚C) v/s Trust force Fz (N)

B. Effect of Variable Parameters:

1) Cutting speed: With the increase in cutting speed till 60 m/min cutting forces decrease and time of machining decrease.
2) Feed: With increase in feed cutting forces are increase and time of machining decrease.
3) Temperature: With increase in temperature for same speed and feed values cutting forces are reducing significantly and machining time decrease which indicates increase in MRR.

VII. CONCLUSIONS

An oxygen- LPG gas cutting torch is used to heat the workpiece for thermally enhanced machining of Ti6Al4V. The material is heated locally near the cutting tool which softens the material along the predefined cutting path. Due to this softening, change in deformation behavior occurs. It reduces cutting forces and higher material removal rate The local temperature of the material as it enters the cutting zone plays an important role in the case of thermally enhanced machining process. This temperature has to be maintained in the optimum range, which is dependent on the actual workpiece material. Position and orientation of the incident flames of oxygen LPG flame are also critical to achieve the maximum benefit from TEM. According to the experimental investigations, it may be observed that that temperature is one of the principle parameters in machining. Besides, some other observations are: Statistically designed experimental study proves that material removal rate increases by TEM in comparison to conventional machining for Ti6Al4V as less time is consumed for each level of temperature while keeping the machining length constant.

Ti6Al4V is well suited for service in elevated temperature and properties of materials are not get much disturbed while machined at elevated temperatures.

In addition, machining time is reduced, which is one the greatest need of the global manufacturing industries; using a laser heating attachment to TEM to avoid the preheating.

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