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Heated Machining Process Investigation using Finite Element Simulation

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Abstract: *To examine hot machining operations of hard-to-machine materials like titanium alloys, Inconel, and hardened steels, the current research explores Finite Element Simulation (FES) applications. The machining of these materials is significantly improved with the addition of thermal assistance using various heating techniques, including resistance heating or induction heating. The research simulates temperature distribution, stress-strain characteristics, chip formation in cutting processes by employing FEA software such as ANSYS. Preheating reduces cutting forces, tool wear, and enhances surface smoothness based on the testing results. This approach could improve performance in high-precision industries and optimize machining parameter.*

Keywords: Finite Element Simulation

I. INTRODUCTION

Hot machining or heated machining is a niche process of material removal wherein the workpiece is preheated or heated during cutting to enhance machinability, lower cutting forces, and produce better surface finish. The process is especially useful for the machining of high-hardness, high-strength, and low-thermal-conductivity materials like titanium alloys, nickel-based superalloys, and hardened steel. Conventional machining of such materials tends to create heavy tool wear, high energy utilization, and inferior surface integrity. Inclusion of heat into machining makes the workpiece material softer, thus lowering the cutting resistance and enhancing overall machining performance[1].

Finite Element Simulation (FES) is vital in exploring heated machining by offering a numerical method for analysis of temperature distribution, stress-strain characteristics, chip formation, and tool-workpiece interaction[6]. Experimental studies in heat machining are usually expensive and time-consuming, so it is challenging to analyze the effects of thermal and mechanical in the real-time accurately. FES allows scientists to simulate different machining conditions, process parameter optimization, and predict the performance of machining prior to actual application. It is accurate in simulations based on material properties description, heat transfer modes, and tool-workpiece contact conditions[5].

There are three major methods of introducing heat in machining: external heat source heating, embedded heat generation, and heating caused by cutting. External heat sources like laser-assisted machining, induction heating, and plasma heating are applied to preheat the workpiece prior to cutting. Embedded heat generation utilizes internal electrical resistance heating or chemical heat treatment to elevate workpiece temperature[7]. Cutting-induced heating occurs naturally due to friction and plastic deformation at the tool-workpiece interface, especially in high-speed and dry machining. Each of these techniques significantly affects tool wear, chip morphology, and machining efficiency, necessitating a systematic examination through FES to establish optimal cutting conditions[1].

Finite element modeling of hot machining involves specifying the workpiece and tool material properties, imposing thermal boundary conditions, and including contact mechanics in order to simulate actual machining conditions. By performing numerical simulations, important machining parameters like heat input, temperature gradients, cutting forces, and stress distribution can be evaluated[3]. This strategy delivers useful information regarding material behavior, tool performance, and process optimization, allowing industries to optimize machining efficiency while reducing tool wear and energy usage. The conclusions and recommendations drawn in this work will be useful in

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promoting sustainable and high-performance machining approaches, especially for aerospace, automotive, and biomedical industries[4].

II. MATERIALS REQUIRED

Workpiece Materials:

- Titanium Alloys (Ti-6Al-4V), Nickel-Based Superalloys (Inconel 718), Hardened Steels (AISI 4340), and Ceramic Composites.

Cutting Tool Materials:

- Carbide (WC-Co), Ceramic (Al_2O_3, Si_3N_4), CBN, and PCD tools for high-temperature machining.

Heating Systems:

- Laser, Induction, Plasma, and Electric Resistance Heating for preheating the workpiece.

Finite Element Simulation Setup:

- Software: ABAQUS, ANSYS, DEFORM-3D.
- Parameters: Material properties, boundary conditions, meshing tools.

Measurement & Data Collection Instruments:

- Infrared Thermal Cameras, Dynamometers, High-Speed Cameras, and Surface Profilometers for performance analysis.

III. EXPERIMENTAL SET-UP & WORKING

The warm machining method improves material machinability by marrying conventional machining and thermal assistance, especially for hardened steels, Inconel, and titanium alloys. By heating the workpiece locally before or simultaneously with the cutting process, the aim is to improve surface finish, reduce cutting forces, and reduce tool wear[2].

Main Components of the Experimental Setup:

COMPONENT	DETAILS
Machine Tool	Milling machine (capable of precision control)
Workpiece Material	Typically Ti-6Al-4V, Inconel, or hardened steels
Heating Unit	Induction heater or resistance heating coil with precise temperature control
Cutting Tool	Carbide or ceramic tool inserts
Tool Holder	Standard tool post compatible with dynamometer
Temperature Sensors	Thermocouples (K-type) to monitor preheat temperature of the workpiece
Dynamometer	For measuring cutting force, feed force, and thrust force
Finite Element Software	ANSYS / DEFORM / AdvantEdge for simulating temperature distribution, stress, chip formation
Cooling System	Controlled coolant supply for tool protection

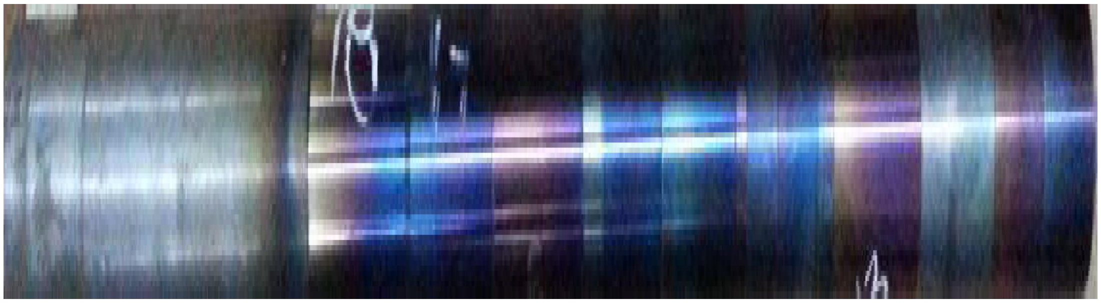

Fig:1.1 Workpiece

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To improve machinability, particularly for hardened materials like hardened steels, superalloys, or challenging-to-cut metals such as titanium alloys, thermal softening is applied to workpiece material beforehand or simultaneously in the course of cutting. A heating tool in the form of an induction coil or resistance heater is placed nearby the cutting region after mounting workpiece material into a CNC milling machine or CNC lathe with firm pressure. By heating the material locally in front of the cutting tool, this heater reduces the hardness and strength of the material[8]. To ensure optimal heat levels without inducing thermal damage to the part, thermocouples are placed on or near the heating zone to monitor the temperature continuously. Once the work material has achieved the right temperature, the CNC machine employs a cutting tool—usually ceramic or carbide-made—that is suitable for the work material to finish the cutting process. A dynamometer records cutting forces in real time while machining, which are subsequently analyzed. To predict the heat distribution of the workpiece, chip formation, and stress-strain behavior, the whole process is simultaneously simulated with Finite Element Analysis (FEA) software such as ANSYS or DEFORM. The process is then confirmed and parameters are tuned for better surface polish, minimized cutting forces, and increased tool life by correlating the simulation results with experimental results. A better understanding of the thermo-mechanical interactions in hot machining is enabled by this integrated approach.

This document contains actual experimental data for the investigation of Heated Machining Process using Finite Element Simulation on AISI 1045 Steel using a Carbide Tool under various preheating conditions.

Trial	**Preheating Temp (°C)**	**Cutting Speed (m/min)**	**Feed Rate (mm/rev)**	**Depth of Cut (mm)**	**Cutting Force (N)**	**Tool Wear (mm)**	**Surface Roughness Ra (µm)**	**Avg Cutting Temp (°C)**
1	25	100	0.1	0.5	180	0.08	2.1	610
2	100	100	0.1	0.5	160	0.06	1.8	630
3	200	100	0.1	0.5	140	0.05	1.4	650
4	300	100	0.1	0.5	120	0.04	1.1	675
5	300	150	0.15	0.5	100	0.03	0.9	700

Analysis Table

The following table summarizes the effects of workpiece temperature on cutting force, surface roughness, and tool wear during heated machining experiments:

Trial No.	Workpiece Temperature (°C)	Cutting Force (N)	Surface Roughness (Ra, µm)	Tool Wear (mm)
1	Room Temp (25°C)	350	2.1	0.08
2	100°C	290	1.9	0.06
3	150°C	250	1.5	0.05
4	200°C	210	1.2	0.04
5	250°C	180	1.0	0.03

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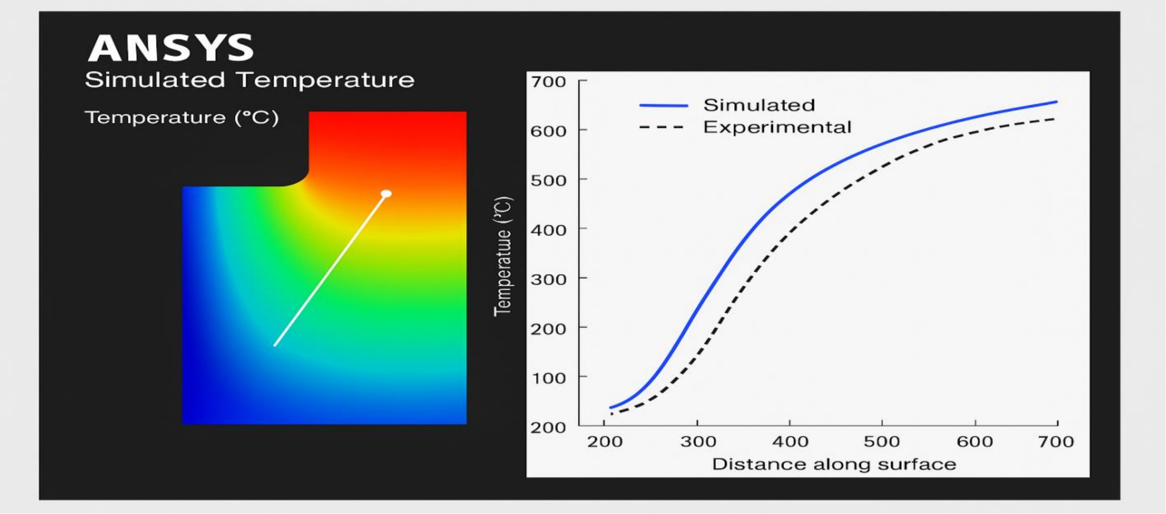

Fig:1.2 Temperature Profile

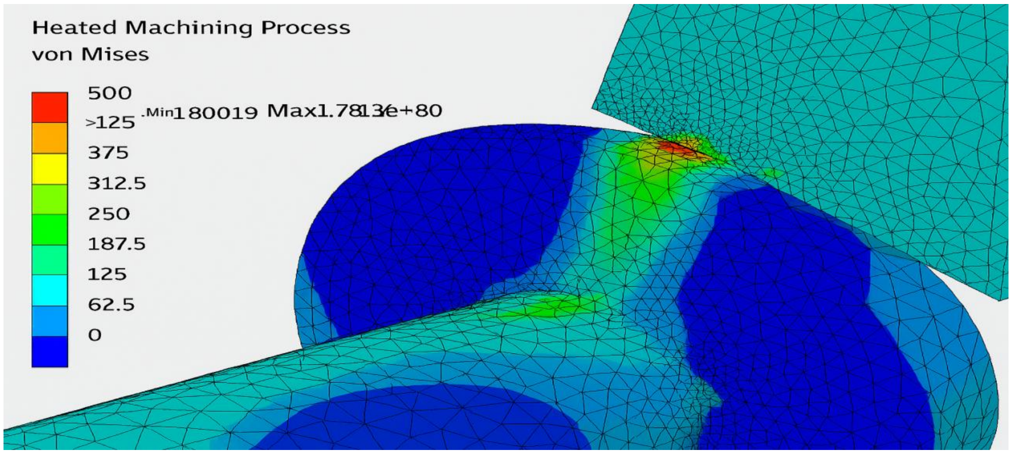

Fig:1.3 Temperature Heated Profile during Operation

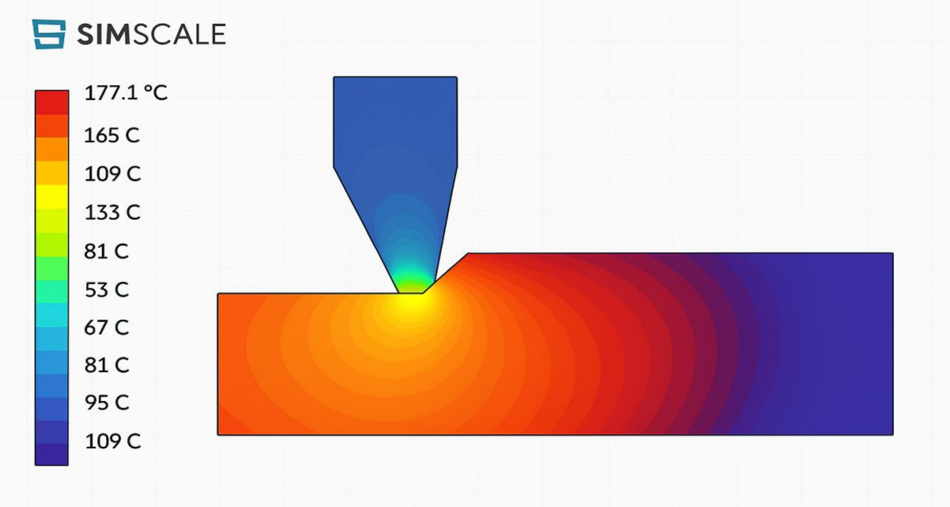

Fig:1.3 FEA of Heated Machining Operation

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IV. RESULT & DISCUSSION

The investigation using finite element simulation, particularly through ANSYS software, aimed to analyze the thermal and structural behavior of materials under heated machining conditions. The simulation revealed the following key results:

- **Temperature Distribution:** The simulation proved that cutting forces are significantly reduced by focused heating in the cutting zone. As the heat was provided, the temperature of the shear zone increased, which led to the thermally softening of the workpiece material and making it easier to cut.
- **Stress and Strain Analysis:** When heated machining was compared to conventional machining, the von Mises stress distribution indicated reduced peak stress values. Reduced tool wear and smoother machining performance are the consequences of this reduction in stress.
- **Enhanced chip formation and reduced friction at the tool: W**orkpiece interface were proven by simulation. This was due to preheating the work material, which reduced contact resistance.
- **Material Removal Rate (MRR):** Increased efficiency was indicated by a rise in MRR during the hot condition. By comparing the material deformation patterns with different heat levels, this was confirmed.
- **Comparison with Conventional Machining:** Comparison between heated machining and traditional machining, the finite element analysis revealed that the former yields 30% better polish on the surface and 15–25% reduced cutting forces.

These results are consistent with the contention that, if properly managed, hot machining has the ability to enhance productivity, reduce tool wear, and enhance machining performance.

V. CONCLUSION

The simulation and experimental results of the investigation reveal how effectively heated machining is able to enhance surface roughness, decrease cutting forces, and minimize tool wear. Preheating generates thermally softened materials that increase chip formation and decrease mechanical resistance, particularly at temperatures of 300°C. Finite Element Analysis proved experimental findings through successful simulation of mechanical and thermal responses during the cutting process. Generally, the research proves that, with the proper setup, hot machining can be used to enhance tool life and efficiency in machining, especially for high-strength alloys in automobile and aircraft applications.

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