DEVELOPMENT OF HIGH PERFORMANCE MACHINING TECHNIQUES THROUGH DATA MINING AND INTERPRETATION: MODELLING FOR TEMPERATURE DISTRIBUTION OF NIMONIC 90

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Abstract- Nickel based super alloys are fast gaining relevance and importance in the aerospace and steam power industries, as they have high strength to weight ratio, and exhibit superior mechanical properties. In addition, they possess high resistance at high temperatures; maintaining their resistance to corrosion, thermal shock, creep and erosion at elevated temperatures. Nickel based alloys contain a high percentage of Nickel and Chromium elements, and a continuous face centered cubic austenitic phase with poor thermal diffusivity, which is formed after various surface treatments. The austenitic phase contributes to the high yield strength and results in poor machinability of Nickel based alloys.

The basic problem in machining of Nickel based alloys is their high chemical activity at high cutting forces and temperatures. Most of the tool coatings (TiN, TiC, TiSn, etc.) have higher chemical affinity with Nickel based alloys. So, chemical diffusion between the tool and the machined work-piece takes place, thus affecting the tool life and machined surface quality. To be able to accurately predict the temperature distribution across the Nickel based work piece, we developed a 3D simulation for temperature modelling of Nimonic 90 during turning and then contrasted the values predicted by the model with the actual experimental values. Tweaking the various variables, we can find out the optimum parameters to be used while machining so as to have the desired temperature distribution across the work piece.

Keywords- Nimonic 90, Temperature Modelling, Experimental Verification, Turning, Machining Parameters, Tool Wear, Deform 2D

Introduction

Nimonic 90 is a recently developed Nickel based heat resistant super alloy, with considerable content of Cobalt and Chromium. Machining of such heat resistant super alloys has been an ongoing research field due to increasing application of these alloys as well as the apparent problems with their processing, owing to their low thermal conductivity and high temperature strength.

Any variations in the machining process of the Nickel super alloys might deteriorate the quality and performance of the products made from them, which is of considerable significance in the aerospace industry. To predict the machining characteristics in advance and help reduce the cost of manufacturing resulting from improper machining, suitable modelling techniques are called for. Modelling is one of the most widely used tools in the study of machining processes due to its several advantages in design, validation and control of the machining process. The numerical simulation instead of relying on experimentation is very useful to predict the thermal and mechanical properties of both the work-piece and tool without spending undue time in experimentation. The accuracy of the simulation depends mainly on the input values which imparts huge importance to understanding how the input parameters effect the predictive machining model.

Vaz et al, (2007) attributed the complexity in modelling of metal cutting to the diversity of physical phenomena available, including thermo-mechanical coupling, contact-friction, and material failure. The large and localized plastic deformation and complex contact conditions are the principal difficulties one faces while modelling machining processes.

Finite Element Modeling is presently the most widely used modelling technique in the machining area owing to advances in the field of software computing. Ezilarasan et al., (2014) attributed the various physical phenomena taking place from micro to macro scale during machining for the interaction between the workpiece and tool becoming very complex and highly stochastic. In addition, several variables like the properties and condition of the work material, tool material, tool geometry, cutting parameters, dynamic performances of the machine tool and clamping conditions are also interlinked. Analysis and control thus naturally become a challenging task in any machining process, but modelling provides a solution to this. Since cutting force and temperature play a prominent role in dictating the performance of the machined surface of the work materials, this paper uses Finite Element Analysis to predict these machining characteristics.

While Lagrangian finite element formulation deforms the mesh grid along with the material, a Eulerian formulation of a continuous medium fixed the grid in space. This paper uses Deform 2D software, based on the implicit Lagrangian computation routine with continuous adaptive remeshing, for the FEM analysis. The Finite Element tool in the software is capable of converting large scale problems in magnitude and complexity into solvable 2D problems. The domain is divided into nodes and elements which store the values calculated at various time intervals during the simulation process. The large non-steady state calculations are reduced to smaller steady state equations and solved one step at a time over the course of the simulation.

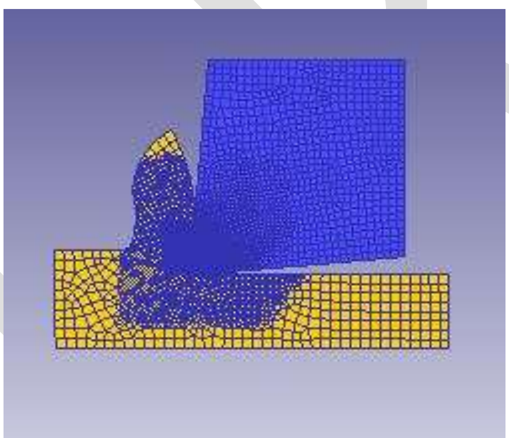

Fig.1: Simulation in Progress in DEFORM 2D

Modelling in Deform 2D occurs in three consecutive steps, Pre-processing, Simulation and Post-processing. The preprocessor uses a graphical user interface to assemble the data required to run the simulation. The orthogonal cutting process is modelled as a plane strain problem which assumes the geometry to have a unit depth with both front and back faces constrained. The simulation assumes that the objects will behave identically in any given cross-section across the width and height of the object. Data on conditions of the process environment, type of physical process and discrete time steps is fed to the pre-processor. It also generates a mesh within the workpiece and tool, after specifying their border geometry and taking data about the mesh density. To perform a simulation, a database containing the process data and simulation controls is prepared. The control, material, object and inter-object options of the preprocessor allow for interactive input of the simulation parameters. The specified database is executed as simulation steps are generated. The results of the simulation are displayed through the post-processor in graphical and alphanumeric form.

Objectives and Deliverables

- *Temperature modelling of Nimonic 90 during turning:* A temperature model would be developed using Deform 2D for accurate prediction of work piece and tool characteristics through simulation.

- *Conducting a comprehensive Force Analysis:* Use the model so developed to measure the forces acting on tool in order to ensure the overall accuracy.

- *Verification of the theoretical model using experiments:* To compare the cutting force curve as well as the temperature profile generated using the theoretical model with the values obtained during experiments.

Literature Review

Nimonic alloys are one class of nickel based super alloys developed to give superior creep resistance and are commonly used in wrought form. Nimonic type alloys gain their superior high temperature properties basically from the precipitation of Ni-Al-Ti compounds within a Ni-Cr matrix. Raman and Padmanabhan, (1995) carried out a comparative study of AISI 304 LN stainless steel and Nimonic 90 under strain cycling and depicted the superior characteristics of Nimonic 90 over AISI 304. They showed the higher energy absorption capacity of Nimonic 90 as well as the fact that it exhibited longer fatigue lives at all strain amplitudes. Nimonc 90 also displayed a much shorted transition life, thus proving its superior credentials.

Maranhao and Davim, (2010) studied the influence of friction coefficient at the tool-chip interface on cutting and feed forces, cutting temperature, plastic strain and strain rate and maximum shear stress during machining of stainless steel. Their experimental validation revealed that friction modelling at the tool chip interface had a significant effect on the values of the modelled cutting parameters. It was thus shown that the friction coefficient has a huge bearing on cutting and feed forces, plastic strain and stress, as well as the cutting temperature and so, must be carefully chosen for precise results.

Numerous research papers have been published to evaluate the machining characteristics of nickel based alloys. Machining characteristics in the case of nickel based alloys take center stage as the life of components manufactured from these alloys depends intimately on these characteristics, which is of significant importance in industries like aerospace and steam power.

Aspinwall et al, (2007) studied the machining of nickel based alloys with profiled super abrasive grinding wheels experimentally while Kortabarria et al, (2011) developed different residual stress profiles using different dry facing conditions for Inconel 718. Wei, (2002) studied the feasibility of using milling or grinding as alternatives for the current EDM process to machine shaped hole in Inconel 718 while Soo. et al, (2011) estimated the machinability and surface characteristics of RR1000 Nickel based alloy in drilling and milling process.

One of the biggest applications of the Nimonic alloys is in the gas turbine aero engine industry, where designs strive to achieve greater power, reduced weight and improved fuel economy. Studies show that under the thermal and mechanical loading conditions experienced by turbine blades, the major deformation mechanisms are creep dominated. Creep life for any material depends intimately on its operating temperatures, and can be said to be halved for every 10-15 degree Celsuis increase in temperature. This highlights the importance of study of the thermal characteristics during machining of Nimonic alloys. G. F. Harrison and T. Homewood, (1994) somewhat successfully demonstrated the use of the Graham and Walles Creep equation to predict the creep characteristics of Nimonc super alloys.

Developing a temperature model for turning of Nimonic 90 makes a study of its hot working characteristics essential. Srinivasan and Prasad, (1995) found the Nimonic alloys to exhibit a high temperature domain representing the process of dynamic recrystallization in their hot working processing maps, which can be attributed to the presence of carbon in the form of interstitials in the alloys. Also, Nimonc 90 was found to exhibit cracking at temperatures of less than 875 degrees Celsius, which is the ϒ' dissolution temperature.

The composition of Nimonic 90 comprises mainly of Nickel, Cobalt and Chromium.

Carbon	0.13 max.
Silicon	1.0 max.
Copper	0.2 max.
Iron	1.5 max.
Manganese	1.0 max.
Chromium	18.0-21.0
Titanium	2.0-3.0
Aluminum	1.0-2.0
Cobalt	15.0-21.0
Boron	0.02 max.
Sulfur	0.015 max.
Lead	0.0020 max.
Zirconium	0.15 max.
Nickel	Balance

Property	Metric	Imperial
Density	8.18 g/cm^3	0.296 lb/in^3
Melting point	1370 °C	2500 °F
Co-Efficient of Expansion	12.7 µm/m.°C (20-100 °C)	7.1x10^{-6} in/in.°F (70-212 °F)
Modulus of rigidity	82.5 kN/mm^2	11966 ksi
Modulus of elasticity	*213 kN/mm^2	30894 ksi
	**227 / 240 kN/mm^2	32924 / 34810 ksi

* Solution Annealed + Aged **Spring Temper and Aged

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Methodology

Before embarking on the modelling and subsequent simulation of our model, we decided to become familiar with the material under study, i.e., Nimonic 90 by reading in depth about it. We became acquainted with the various uses of the material, as well as the numerous problems faced while machining it in order to derive relevance of its temperature modelling. We then conducted extensive research detailing the effect of various turning parameters on the temperature profile of the work-piece and read about the research work being done on developing temperature profiles during machining of other Nickel based work-pieces. This extensive literature review enabled us to become familiar with the material as well as the process and the subsequent effects of varying parameters.

The next objective was to develop a theoretical model that could accurately depict the temperature profile of the work-piece with varying process parameters. Firstly, the super alloy's composition as well its physical properties as a function of temperature were procured and then used to define Nimonic 90 as a new material in the software. The tool insert to be used for experiments was then finalized to be CNMG 120408-THM, a high performance Tungsten Carbide (WC) insert. Its geometrical properties were then found and used to design the insert in the SolidWorks CAD package. The simple workpiece designer provided in Deform 2D was used to develop a prototype of the work piece as temperature profile is largely independent of the size of the workpiece.

The default temperature of both the workpiece and tool was taken to be 35 degrees Celsius. Since no lubricants were used during experimental validation, the heat transfer coefficient was taken at its default value of (45 N/sec/mm/C) while the friction coefficient was modified to 0.6 as this displayed the best correlation with the experimental results. The mesh density was taken to be 2000 for the tool insert, with relative positioning while the workpiece had 25 elements through uncut chip thickness. The simulation steps were taken to be 1500, with data being saved after every 10 steps. For calculating the tool wear, the following model was used.

$$w = \int apVe^{-b/T}\,dt$$

P = interface pressure;
v = sliding velocity;
T = interface temperature (in degrees absolute);
dt = time increment;
a,b = experimentally calibrated coefficients

After careful setup of all the input parameters, the model was then simulated to generate the temperature profile, load diagram, the stress map, strain and velocity profiles among other information.

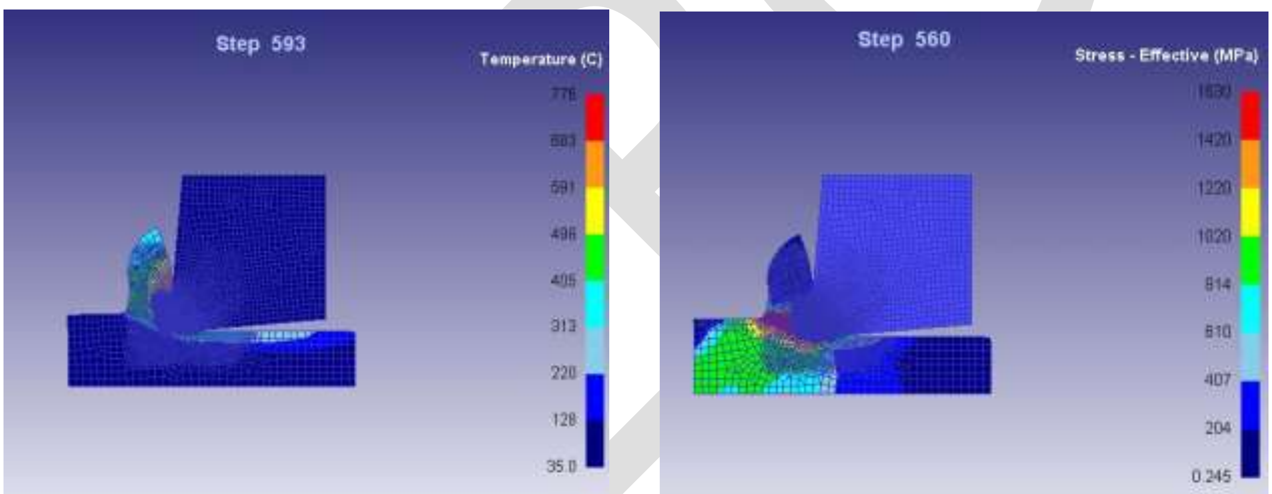

Fig. 2: a) Temperature Profile, b) Effective Stress Map developed using theoretical model at Vc = 40m/min and Feed Rate = 0.12 mm/rev

The modelling was done across a 5*5 matrix, with cutting velocity varying from 20 m/min to 100 m/min and the feed rate changing from 0.06 mm/rev to 0.14 mm/rev. For the purpose of experimental validation, observations were taken only across a 2*2 matrix with cutting velocity at 40 m/min and 60 m/min and the feed rate at 0.06 mm/rev and 0.08 mm/rev. Any more experimental data would have been redundant since if the model correlated well with the experimental results for these input parameters, it would be a reliable model and would be able to predict accurately the characteristics for other input parameters too.

Due to a lack of hardware, the temperature profile validation was unfortunately not possible. Resultantly, only the cutting forces analysis using a Kistler piezo- electric tool post dynamometer was conducted with a Nimonic 90 work piece and CNMG 120408-

THM insert. The resultant cutting force curves were recorded and compared with the theoretical model's predictions for similar input parameters.

Results

As predicted by the model thus developed, the work piece temperature variation with time has been plotted for a constant cutting speed of 20 m/min and feed rates varying from 0.06 mm/rev to 0.14 mm/rev. As Fig 3. Clearly depicts, the work piece temperature rises with increasing feed rate for a constant cutting velocity, which correlates well with the experimental results and is consistent with the theoretical background.

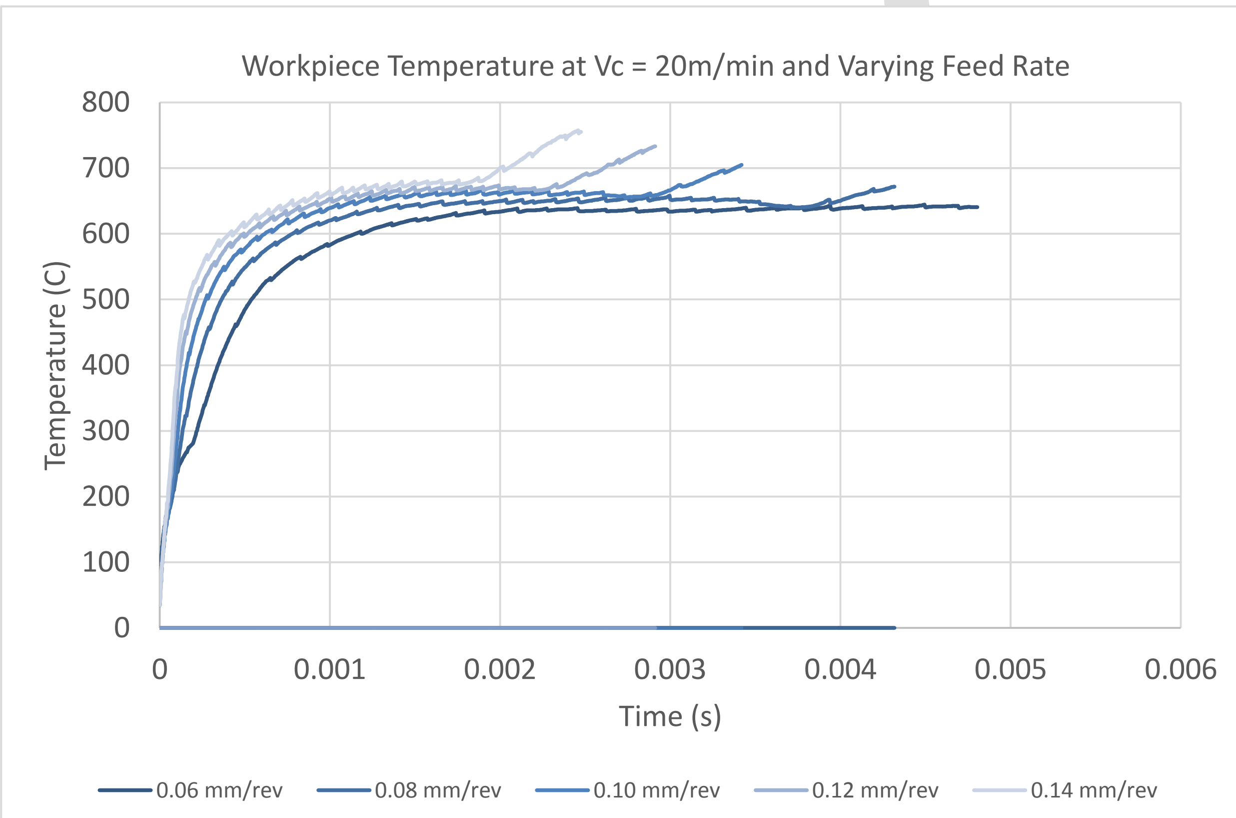

Fig. 3: Workpiece temperature at constant cutting velocity and varying feed rate

A plot of the work piece temperature at a constant feed rate of 0.08 mm/rev and increasing cutting velocity has been plotted in Fig. 4. As expected, the work piece temperature rises with rising cutting velocity due to the generation of increasing frictional force. A notable observation is that the work piece temperature distribution is more diffused and spaced for the varying cutting speed case as against the varying feed rate case where the curves almost coincide.

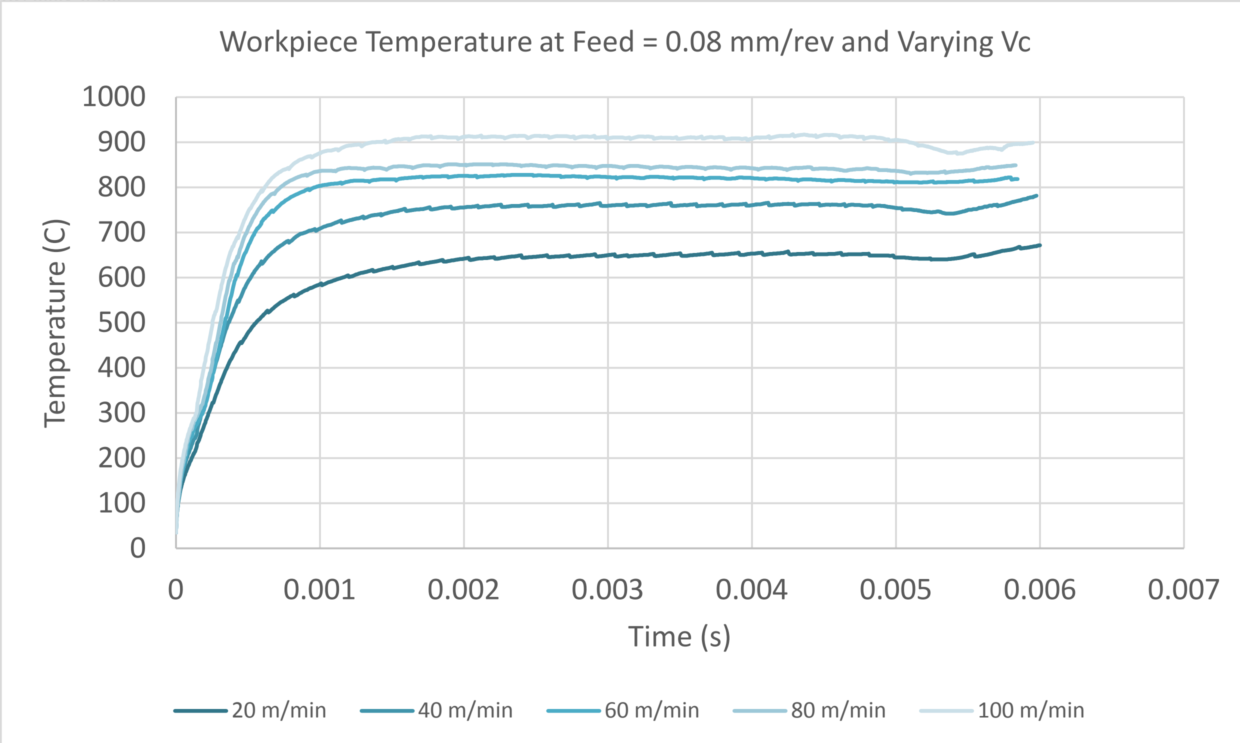

Fig. 4: Workpiece temperature for varying cutting velocity and at a constant feed rate

Similarly, the tool temperature for constant cutting speed and varying feed rate as well at constant feed rate and varying cutting velocity has been plotted in Fig. 5 and 6 respectively. They show a similar trend as for the workpiece, that is, the temperature rises with increasing cutting velocity as well as feed rate. This is to be expected as has been shown in numerous experiments historically and has been proven through several theories.

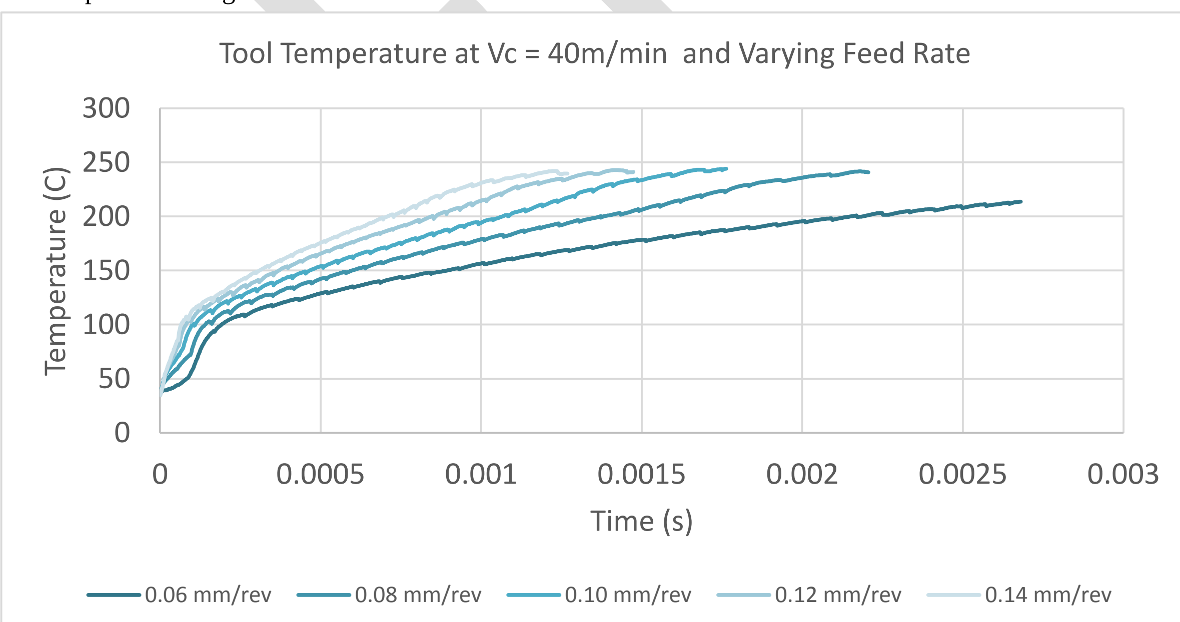

Fig. 5: Tool temperature at constant cutting velocity and varying feed rate

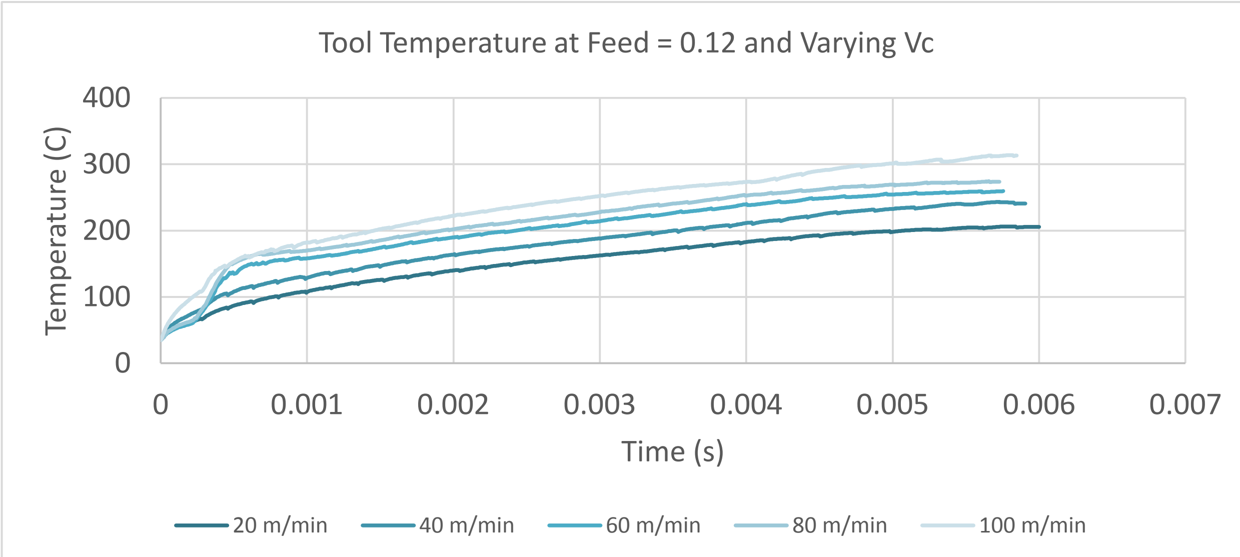

Fig. 6: Tool temperature at constant feed rate and varying cutting velocity

	0.06 mm/rev	0.08 mm/rev	0.10 mm/rev	0.12 mm/rev	0.14 mm/rev
20 m/min	640.4	671.8	704.8	733	757.7
40 m/min	758	781	807.5	839.4	860
60 m/min	821	825.6	839.1	849	853.3
80 m/min	847.1	849.4	864	875.2	880.4
100 m/min	911.4	916	919	946.4	953

Fig. 7: Maximum Work-piece Temperature with varying Cutting velocity and Feed rate

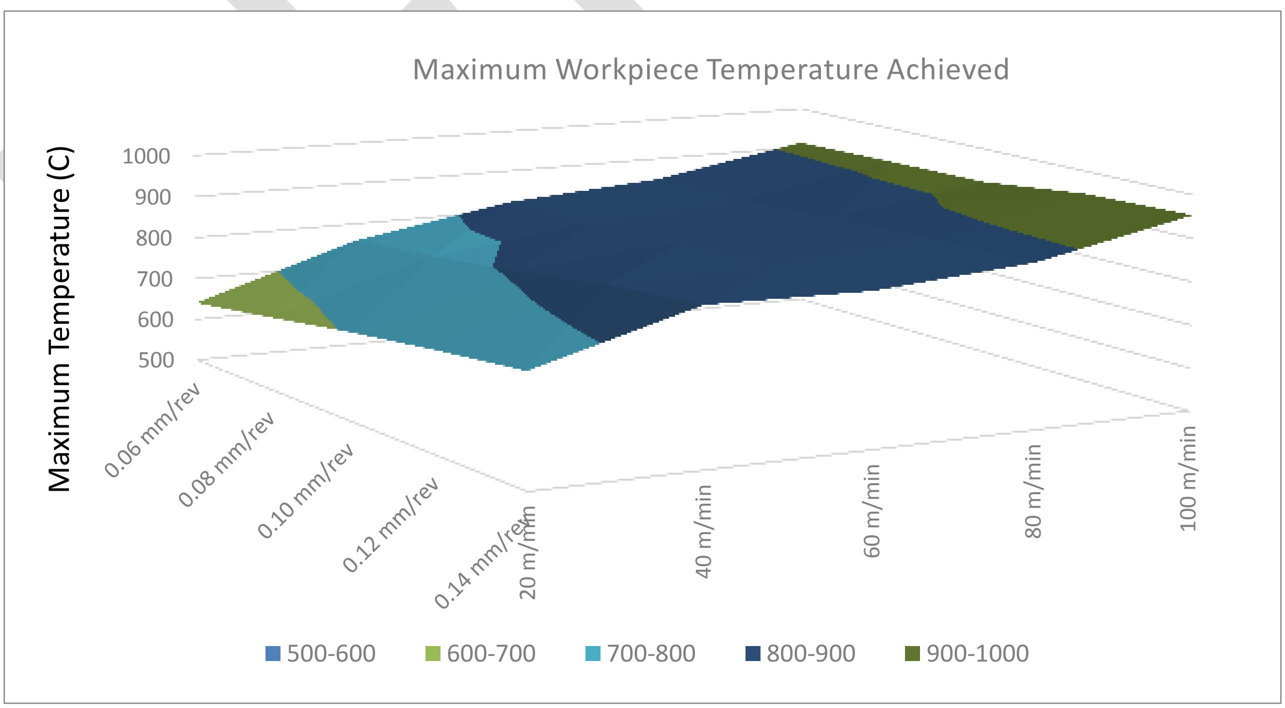

Fig. 8: 3D Plot showing the variation of Maximum Work-piece temperature with Cutting Velocity and Feed Rate

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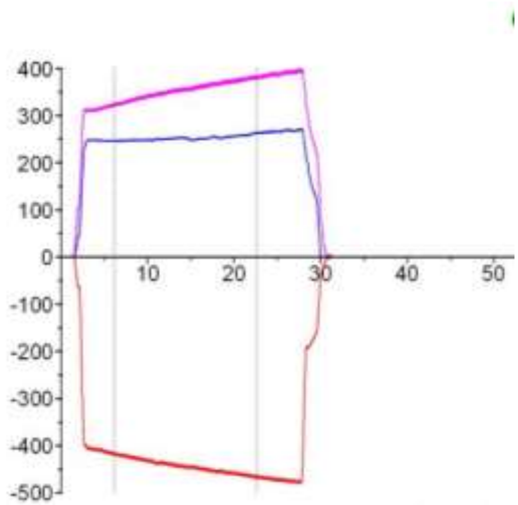
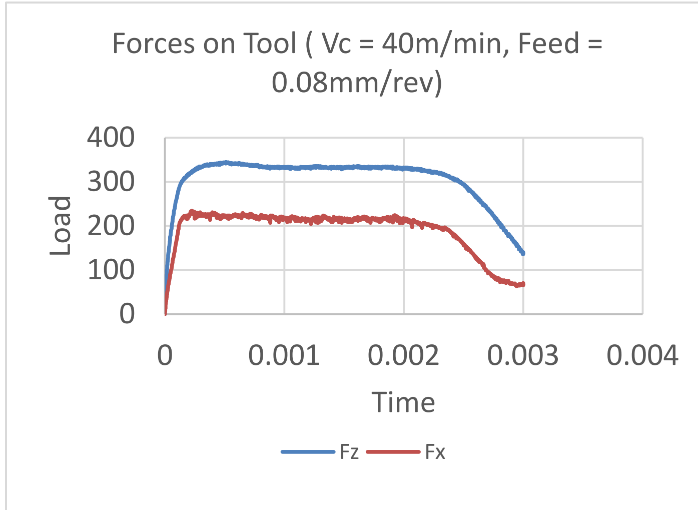
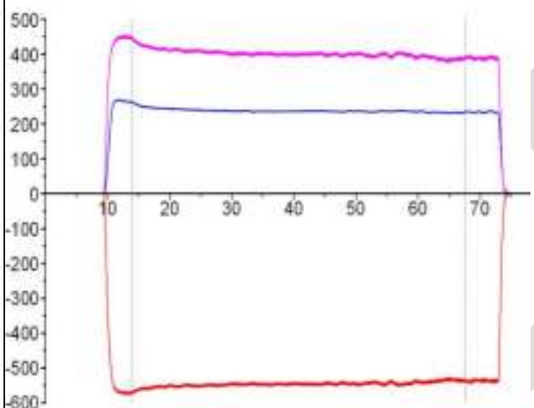






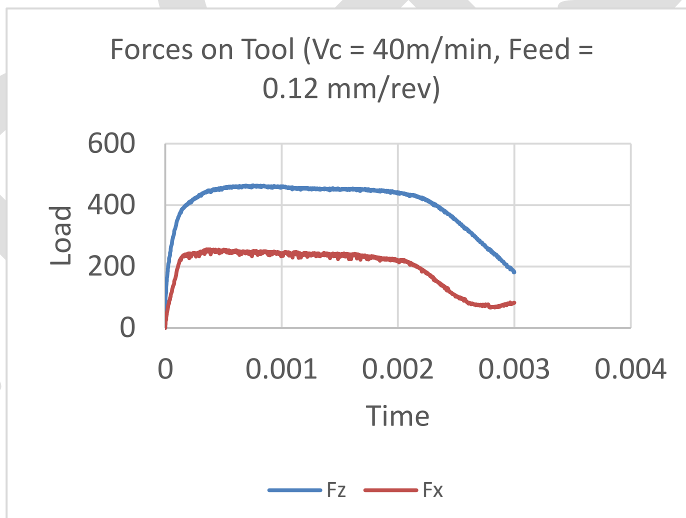
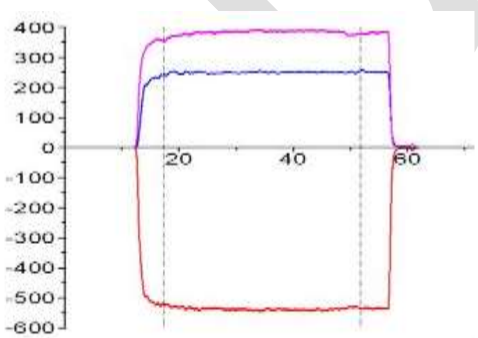


Fig. 10



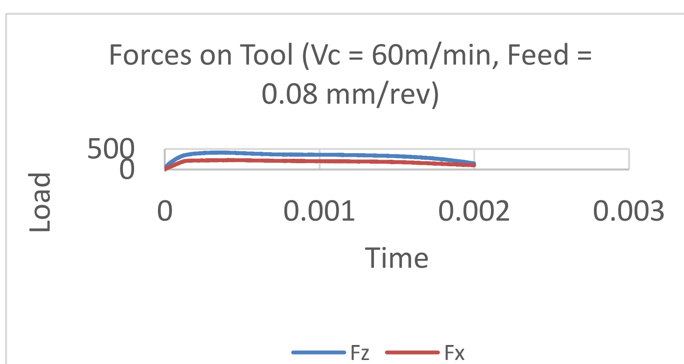
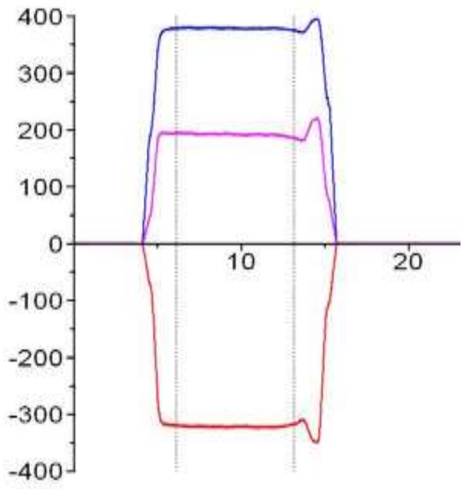


Fig. 11



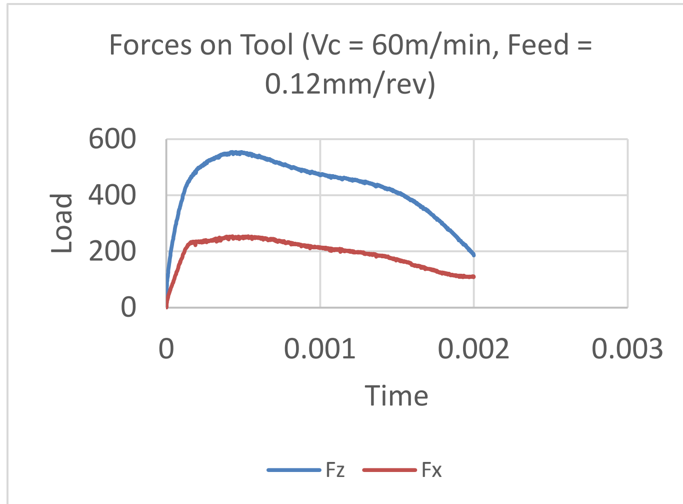


Fig. 12

Figures 9, 10, 11 and 12 show the experimental observations as well as the theoretical predictions for the forces acting on the tool for a 2*2 matrix of varying cutting velocity as well feed rate. The figures clearly depict that the theoretical predictions for the cutting forces are quite close and within the margin of error, thus correlating well with the experimental findings. The cutting forces show a marked increase with rising feed rate for a constant velocity while they are almost constant when the feed rate is held constant and cutting velocity is increased. This is consistent with the theoretical background of the effect of cutting velocity and feed rate on the cutting forces. The model thus turns out to be quite reliable while simulating and predicating the cutting forces.

Conclusion

While the experimental validation for temperature profiling could not be conducted due to lack of appropriate hardware, it can be concluded that since the model correlates well with the experimental results for cutting speed and proves to be quite reliable, it is expected to be accurate while predicting temperature profiles too. The model thus developed is quite consistent with experimental findings and may well be used in the future for accurate prediction of temperature and cutting forces during turning of Nimonic 90.

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