Determination of Optimal Cutting Conditions in Orthogonal Metal Cutting Using LS-DYNA with Design of Experiments Approach.

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Abstract

Optimal selections of cutting conditions contribute significantly to the increase in productivity and reduction in costs of machining processes. The main objective of the present paper is to explore the resultant temperature formed due to complicated interactions and between rake angle, depth of cut and cutting speed. Finite element simulations using LS-DYNA is used as a numerical experiment in the construction of a Design of Experiment (DOE) empirical model of orthogonal machining process. This DOE model is then used to study the temperature formation in the work piece with respect to parameters such as speed, depth of cut and rake angle. The results are also compared with experimental results which have been done already.

Introduction

In many cases, the temperature was a limiting factor of cutting tool efficiency [1,3,6]. When cutting some very hard materials sufficient cutting heat is needed to soften the work piece material. In this process, an ideal machining temperature would generate local ductility for the work piece material without causing significant deterioration of the tool strength. Many important processes like chip formation, tool wear, and surface finish are dependent on temperature formed during machining process. Temperature distribution in a work piece and tool face are studied with an objective to reduce temperature flow in to the work piece thereby reducing thermal distortion of work piece, increasing tool life and reducing the amount of cooling used or to perform dry cutting.

LS-DYNA is used a numerical experiment to perform computational modeling and also to construct Design of Experiment (DOE) empirical model of orthogonal machining process. DOE is a proven way to identify and understand how process factors like cutting speed, depth of cut, rake angle, tool nose radius etc and their combinations affects output temperature. With this information, one can develop the optimum balance between factors and achieve major improvements in reduction of temperature formation while machining.

Much effort has been taken in the past to reduce temperature formation and temperature fluctuation in the tool and work piece while machining. The effect of cutting speed and chip thickness on temperature formation and a hot spot exit in the distribution of the temperature into the chip during the cutting process was studied using pyrometric measurements [8]. Stress and temperature distributions through the primary shear zone and the chip/tool contact region was studied using an elasto-plastic FEA package by Toman Macginley and John Monaghan [9]. Jaspers and Dautzenberg [11] have concluded that strain rate and temperature dramatically influence the flow stress of metals steel AISI 1045 and aluminum AA 6082 –T6, according to measurements with split Hopkinson pressure bar (SHPB) tests.

The Finite Element Model

Finite Element Modeling of chip formation in an orthogonal machining process offers easy means of measuring temperature, strain rates, and stress distributions etc which occur during the machining process. Lagrangian formulation is used in which the mesh is "attached to the work piece". The tool or work piece is advanced through predefined displacement increments, and the finite element solution is obtained. The problem in consideration is studying temperature formation in high speed machining of 6061-T6 aluminum alloy.

Only a small part of the work piece (5 x 0.5 x 1.0 mm) is considered for modeling. A mesh of total 23100 nodes and 43842 elements is used. Displacement boundary conditions are, bottom and side faces are fixed. In this regard, care is taken not to over constrain the cut part of the work piece. So some distance is left from the fixed faces to the cut area with additional computational expense (can be seen in the side view of the mesh). The initial temperature in the tool and work piece is set to room temperature. The tool is given a uniform linear motion in the X direction.

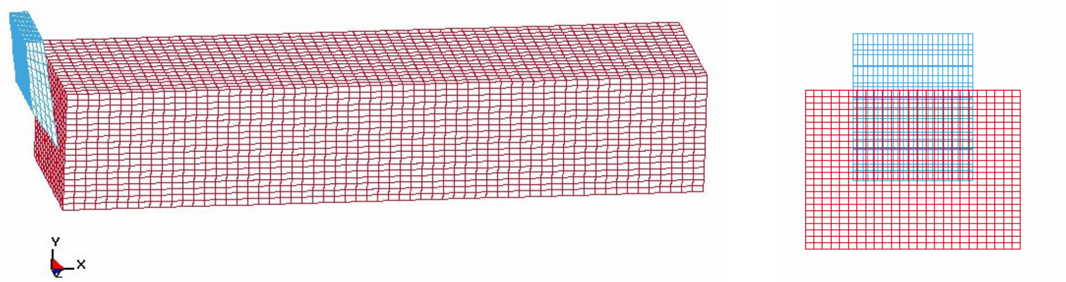


Figure 1: Finite Element Mesh of the Tool and Work piece

The following assumptions were made in regard to this model:

1. Cutting Speed is constant per run.
2. The tool is perfectly sharp
3. The work piece material is a homogeneous polycrystalline and isotropic
4. The cutting is performed in air with no liquid coolants
5. There is no tool wear
6. The tool is rigid (no deformation)

Constitutive Law

Johnson and Cook Constitutive Model:

Material Type 15: Johnson/Cook strain and temperature sensitive plasticity is used because, the strain rates vary over a large range and adiabatic temperature increases due to plastic heating causing material softening. A fully Visco plastic formulation is used which incorporates the rate equations within the yield surface. An additional cost is incurred but the improvement in results can be dramatic. [5].

To model the high strain, strain rate and temperature formation in the work piece, the Johnson and Cook constitutive model was used. The five parameters of Johnson cook model are A – yield stress constant, B - Strain hardening constant, n – strain hardening exponent, C – Strain rate hardening constant, and m – temperature dependent coefficient.

Johnson and Cook express the flow stress as

$$\sigma_y = \left(A + B\bar{\varepsilon}^{p^n}\right)\left(1 + c\ln\varepsilon^*\right)\left(1 - T^{*^m}\right)$$

Where A, B, C, n, and m=input constants , $\bar{\varepsilon}^p$ effective plastic strain

$\dot{\varepsilon}^* = \dfrac{\dot{\bar{\varepsilon}}^p}{\dot{\varepsilon}_0}$ effective plastic strain rate for $\dot{\varepsilon}_0 = 1\ \mathrm{s}^{-1}$

T^* = homologous temperature = $\dfrac{T - T_{room}}{T_{melt} - T_{room}}$

Strain at fracture is given by

$$\varepsilon^f = \left[D_1 + D_2 \exp D_3\sigma^*\right]\left[1 + D_4 \ln\dot{\varepsilon}^*\right]\left[1 + D_5 T^*\right]$$

where σ^* is the ratio of pressure divided by effective stress

$$\sigma^* = \frac{p}{\sigma_{eff}}$$

Fracture occurs when the damage parameter

$$D = \sum \frac{\Delta\dot{\varepsilon}^p}{\varepsilon^f}$$

reaches the value of 1.

The spall models are used to represent splitting, cracking, and failure under tensile loads for solids. The spall model chosen for modeling the metal cutting was the hydrostatic tension spall model. The model induces spall if the pressure becomes more than the specified limit, p_{cut}, which was set as the yield strength of the material.

Equation of State:

Johnson and Cook mode is a hydrodynamic material model that requires an equation-of-state (EOS) to define the pressure-volume relationship. All other constants of the linear equation of state model was set to zero except C_1 which was set equal to the elastic bulk modulus.

Heat at Tool/Work Interface

Temperature rise in metal cutting is caused by two principle heat sources – the first resulting from plastic deformation developed at the primary shear plane *(the shear zone heat source)* (fig 2) and the second due to the friction at the tool-chip interface [7]. Because of the very large amount of plastic strain, it is unlikely that more than 1% of the work done is stored as elastic energy, the remaining 99% going to heat the chip, the tool and the work material [1]. High pressure/temperature causes adhesion of asperities between the tool and the chip there by increasing tool wear. The chip formation process is highly complex and is governed by mechanisms which are not yet fully understood. Material is not really cut away from a work piece and is deformed plastically and sheared away from the remaining metal. As metal approaches the rake face of the tool, it passes through a primary deformation zone (fig 2) which can be modeled as a plane. It is in this region that it changes direction, and undergoes *adiabatic shearing*. That is, although the region is of an extremely elevated temperature, it is transferring little (or no) heat to or from its surroundings while the material deforms in shear parallel to the shear plane angle. The resultant temperature is formed due to complicated interactions and between rake angle, depth of cut, tangential force, tool nose radius and numerous other factors. Only the effect of rake angle, cutting speed and depth of cut is studied. Less energy is dissipated in the secondary shear zone because there is a much smaller volume of material involved, but very high temperatures can be created there.

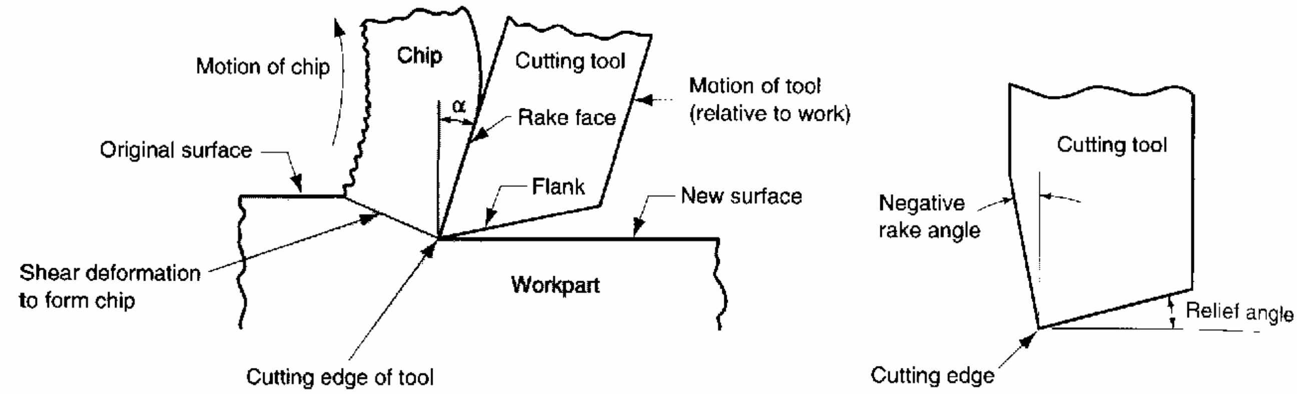


Figure 2: Metal Cutting Diagram

Comparison Of FEA And Experimental Results:

Table 1: Comparison of FEM and Experimental Results

S. No	Rake Angle degrees	Cutting Speed m/sec	Depth of Cut mm	Temperature Experimental [10] °c	Temperature FEA °c
1	5	15	0.5	181	167.60
2	5	15	1.5	238	237.80
3	5	45	0.5	290	247.00
4	15	45	0.5	200	186.80

Design of Experiments approach

Design **O**f **E**xperiments (**DOE**) is a powerful statistical technique to study the effect of multiple variables simultaneously. DOE approach is used to study the effects of multiple factors (cutting speed, depth of cut, and rake angle) on the performance effects (Temperature).

The projected experiment is a test or series of tests in which deliberate changes are induced in the variables of input (signal factor) of the process, so that it is possible to observe and identify the changes in the output (response).

DOE using Taguchi approach attempts to increase the consistency of performance. Consistency is achieved when variation is reduced. The prime motivation behind the Taguchi experiment design technique is to achieve reduced variation (also known as *Robust Design*).

Taguchi Method

Before beginning the experiment, it is important to plan the nature and number of the tests. During the experiments, the process is monitored carefully, to guarantee that everything is made in agreement with the plans, to reduce mistakes in the experimental.

3^2 factorial design for three factors

Factorial designs are widely used in experiments involving several factors where it is necessary to study the joint effect of the factors on a response.

Three parameters were selected to study their influences on temperature formation at a particular point at a distance in the work piece. These parameters include: cutting speed, depth of cut, rake angle. Each parameter has two values, also called two levels.

These values are shown in table 1. The designed orthogonal table L4 (2^3) was used. L4 indicates that there are four parameters, each parameter has two levels and eight combinations are possible.

Taguchi Matrix for 2^3 factorial design

Although the concept of DOE is reasonably straightforward, choosing the most appropriate table and interpreting the results can be more difficult in forming the initial model for the experiment, we choose the full model, that is all main effects and interactions, provided at least one of the design points has been replicated. Highest temperature at the tool-chip interface is obtained through LS-DYNA Finite Element simulations. Average Temperature is got from the observed five replicates. High and Low levels are represented as –1 and +1. They are 5^o , 15^o for rake angle, 14 , 45 m/sec for the cutting speed and 0.5 and 1.5 mm for the depth of cut.

Table 2: Taguchi Matrix

	A	**B**	**C**	**AB**	**AC**	**BC**	**ABC**	Avg Temp ^oC
(1)	-1	-1	-1	1	1	1	-1	167.60
a	1	-1	-1	-1	-1	1	1	136.40
b	-1	1	-1	-1	1	-1	1	247.00
ab	1	1	-1	1	-1	-1	-1	186.80
c	-1	-1	1	1	-1	-1	1	237.80
ac	1	-1	1	-1	1	-1	-1	220.40
bc	-1	1	1	-1	-1	1	-1	395.00
abc	1	1	1	1	1	1	1	335.00

a = rake angle (degrees)
b = cutting speed (m/sec)
c= depth of cut (mm)

Analysis of Variance

The influence of factors on the variation of results -- in terms of discrete proportion -- can only be obtained by performing **AN**alysis **O**f **V**ariance (ANOVA). To determine the most desirable condition in cases in which interaction is found to be significant, analysis of interaction between factors has to be included. The traditional method of calculating average factor effects and thereby determining the desirable factor levels (optimum condition) is to look at the simple averages of the results. Although average calculation is relatively simple, it doesn't capture the variability of results within a trial condition. A better way to compare the population behavior is to use the mean-squared deviation, which combines effects of both average and standard deviation of the results.

Level of Significance in the above analysis was set to 0.05. $M.S_{\text{Factors}}$ (Mean Square) >> $MS_{\text{Error,}}$ Therefore the factors are having an effect on the responses.

Table 3:Anova Table

Sources	SS	df	MS	F	F table	Stat sig ?	α
A	17808.40	1	17808.40	951.05	4.15	*	0.05
B	100801.60	1	100801.60	5383.26	4.15	*	
C	126787.60	1	126787.60	6771.03	4.15	*	
AB	3204.10	1	3204.10	171.11	4.15	*	
AC	122.50	1	122.50	6.54	4.15	*	
BC	12602.50	1	12602.50	673.03	4.15	*	
ABC	115.60	1	115.60	6.17	4.15	*	
Error	599.20	32	18.72				
Total	262041.50	39					

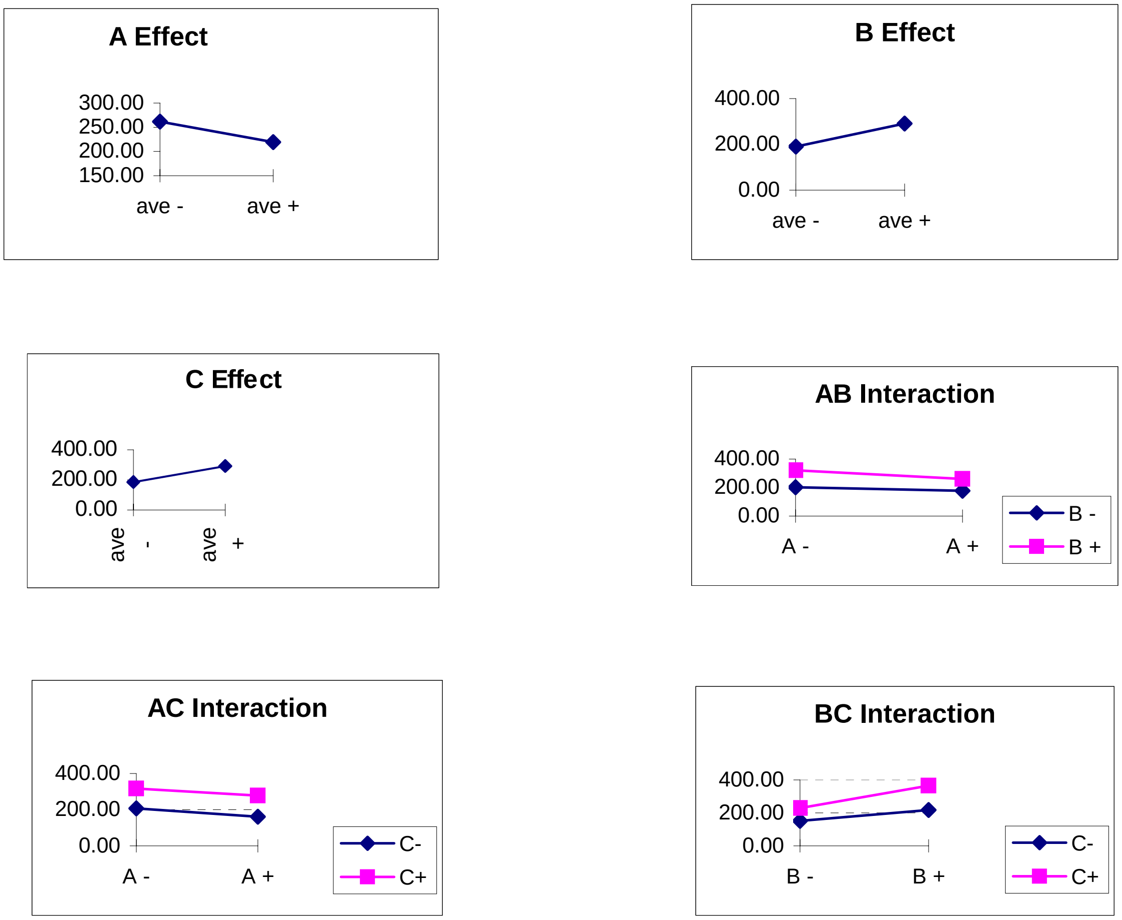
It can be observed from the high SS and F values that depth of cut and cutting speed are the most contributing factors for temperature formation. The effect of tool rake angle (from 5 to 15^o) is not significant. There is less difference between F_{table} and F values for AC and ABC. So, these factors can be eliminated.

Interaction Effects:

If we could only look at main effects, factorial designs would be useful. But, because of the way we combine levels in factorial designs, they also enable us to examine the interaction effects that exist between factors. An *interaction effect* exists when differences on one factor depend on the level you are on another factor. When there is an interaction, it is impossible to describe the results accurately without mentioning both factors. Interactions help us to find which variables need to be altered at the same time to get a particular result, and it may be worth quantifying these interactions.

From the plot of interaction effects, there is no significant interaction between the factors, implying that it is possible to specify the effects of the factors individually. Also it can be observed from the individual plots and combined plots of interaction effects, that for minimum temperature formation, the cutting speed, depth of cut should be kept at a minimum and rake angle should be kept maximum (15^o).

Plot No 1: Interaction Effects



Concluding Remarks

From the above results it is clear that:

The most important main factors are cutting speed and depth of cut. Depth of Cut is the most important factor for temperature formation compared to Cutting Speed. Rake angle is the least important input factor.

Therefore the depth of cut and cutting speed should be kept to a optimum minimum (for machining 6061-T6 aluminum alloy).

Careful examination of the results shows that it is best to have one of these variables set high and the other low.

It should be noted that the results are valid only for machining 6061-T6 aluminum alloy. Other factors such as the surface of the work piece may be harder than the rest of the work piece, tool chatter can occur at low cutting speeds, the extremities of the levels considered for the present analysis, the assumptions holds only for the ideal assumptions etc should be considered.

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