

OPTIMIZING MACHINING PROCESSES FOR PRECISION: AN EXAMPLE USING CALCULATED CUTTING FORCES

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INTRODUCTION

Machining process research is often directed at improving the material removal rate. However, there are some cases where the more precise one makes the component the more valuable it becomes, and so the question is: how precise can you make the part? The effect of the cutting process on the part's precision becomes the priority, not the material removal rate.

Designing a machining process for maximum precision is a motivation for cutting mechanics research. To quantify the machining process effects on the component precision, such as part deformations from cutting forces, requires understanding of the physics of the process.

Calculating cutting forces requires an adequate constitutive material model (relationship of stress-to-strain) for the work piece material. For conditions encountered in machining, this stress-strain relationship is not readily available for even common materials. A pulse-heated Kolsky bar, an experimental method being developed at the National Institute of Standards and Technology (NIST), is directed at obtaining this relationship. This same material model relating stress to strain at high temperatures is valuable when studying other high strain rate problems such as impacts and explosions.

BACKGROUND: MAXIMUM REMOVAL RATE

Optimizing a machining process for maximum material removal rate has been an ongoing research effort since the beginning of the industrial revolution. The problem can be stated in terms of an objective function describing the removal rate for a turning operation, such as:

$$Q_M = t_o \cdot w \cdot V_c \quad (1)$$

Where Q_M is the material removal rate (mm^3/s), t_o is the uncut chip thickness, or the feed per revolution (mm), w is the chip width (mm), and V_c is the cutting velocity (mm/s). This expression describes the material removal rate

for a simple turning operation, but a similar, relatively simple expression can be written for milling or grinding processes. The maximum, or optimum, removal rate is found within given boundaries, or constraints, such as power and speed limits of the machine tool. Also, there are process limits such as tool wear and the effects on part accuracy that can limit the removal rate. The optimum conditions can be found by a trial-and-error approach of calculating the removal rate for all possible parameter combinations within the constraints and looking for a maximum; however, more sophisticated mathematical methods can also be used. As part of the NIST Smart Machining Systems (SMS) Program a robust optimizer has been developed [1]. The NIST optimizer uses a linear programming approach and also handles uncertainties of each constraint and hence determines a "robust optimum."

Addressing part precision with the highest priority requires a different approach than optimizing on material removal rate. For example, increasing cutting speed increases the removal rate, but simply increasing or decreasing the cutting speed does not necessarily affect the precision of the part—additional understanding of the process is required to determine what parameters affect precision.

EXAMPLE: SHELL COMPONENT

An example component will be used to illustrate a method of studying one aspect of the precision of a machining process. The part is a cylindrical thin-walled shell. For this example, let us assume that the required material is aluminum and that the length and inside diameter of the shell are given (100 mm length and 20 mm diameter inside), but the outside diameter of the tube is not specified. The question asked is: how thin can we make the wall and still have the shell as nearly perfect as the machine is capable of making? It is an open-ended question that is frustrating for one working in a job shop

environment. However, the question is not unusual for one involved in precision engineering.

ERROR BUDGET APPROACH

An error budget is a valuable tool when answering the question: how do we improve the process of making a particular part? For example, improving the machine tool precision may not significantly improve the precision of the part if the major sources of error are from the machining process itself. We need to know the relative importance of various contributions to the overall inaccuracies of the part. An error budget is used to identify different error sources and tabulate their effect on part accuracy. We can consider the cylindricity of the outer surface of the shell due to machine tool errors and deflections due to the forces generated in cutting. The end of the tube will be larger if cutting forces are high because the tube will deflect away from the tool. There are other items like distortions due to residual stress and vibrations that would be included in a more complete analysis. As the method is carried on further, additional items can be added and compared.

The effects of relevant machine tool errors, such as the parallelism of the spindle to the axis travel and the error motions of the spindle, can be estimated for the accuracy of a particular part such as our example case. These errors might be on the order of 1 μm for a very high-precision machine tool. However, to quantify the errors due to the deflections, we need to estimate the values of cutting forces.

CALCULATING CUTTING FORCES

For well-established processes, calculating the cutting forces may not be necessary—they have either been measured or “the old-timers” know that they are not significant in making this kind of part. However, when the component is being fabricated the first time, or the material has been changed, or the question is asked “how accurate can you make this part?”, calculating the cutting force is necessary. The problem is not simple and no exact mathematical expression for cutting forces is available, although good predictions can be made by several different types of models, including the finite element method (FEM). Any of the methods require knowledge of the material behavior.

For the example presented in this paper, let us consider machining the part by simple turning and further assume that the cutting geometry is close enough to the orthogonal geometry for practical purposes. Then, cutting forces can be estimated by a traditional model presented by Eugene Merchant and others in the 1940s and described in many machining textbooks, such as Kalpakjian [2]. Using this approach the cutting force can be expressed as:

$$F_C = \frac{w \cdot t_0 \cdot \tau_{flow}}{\sec(\beta - \alpha) \cdot \cos(\phi + \beta - \alpha) \sin \phi} \quad (2)$$

Where F_C is the cutting force in the direction of the cutting speed, w is the width of the cut, t_0 is the depth of cut (or uncut chip thickness), τ_{flow} is the shear flow stress for the work piece material (assuming perfectly plastic material behavior), β is the friction angle (where the coefficient of friction, $\mu = \tan \beta$), α is the rake angle of the cutting tool, and ϕ is the shear plane angle. The thrust force, F_T , can be expressed as:

$$F_T = F_C \cdot \tan(\beta - \alpha). \quad (3)$$

For the special case where the friction angle is equal to the rake angle, the force acting normal to the surface, the thrust force, would be zero. If we assume a coefficient of friction of 0.2, this would make the rake angle, $\alpha \approx 11^\circ$, which is reasonable for a tool cutting aluminum. Therefore, by designing the tool with a rake angle of about 10° , the thrust force would be at least close to zero. Because of the uncertainty of the coefficient of friction, assume $F_T \approx \pm 0.1 \cdot F_C$ for our error budget estimates. The thrust force could actually be either positive or negative, making the cylindrical part either larger or smaller at the end farthest away from the holding chuck.

Determining the shear plane angle has always been a challenge, but a traditional approach finds the shear plane angle to be $\phi = 45^\circ + \alpha - \beta$. For our special case of $\alpha = \beta$ the cutting force expression then reduces to:

$$F_C = 2 \cdot w \cdot t_0 \cdot \tau_{flow}. \quad (4)$$

For this approach, we assume that the cutting geometry is simple and the material behavior can be expressed as a perfectly plastic response. This approach greatly simplifies the problem and makes it possible to get a reasonable value of the cutting force for given cutting conditions, assuming that we know the flow stress for the material. This can be thought of as only a starting point, and a more complete calculation could be performed using an FEM code. The FEM approach could handle more detailed geometry and would require a more complete constitutive material model.

DYNAMIC MATERIAL PROPERTIES

It would be nice if one could look up in a handbook the flow stress necessary for the expression in equation (2) above. The problem is that machining processes produce very high strains, very high strain rates, and also high temperatures with high heating rates.

A method traditionally used for obtaining dynamic material properties is the Split Hopkinson Pressure Bar, also referred to as a Kolsky Bar. This method uses two long bars with a sample of the test material sandwiched between the ends of the bars. A compression strain wave is initiated in the first bar (incident bar) which compresses the sample and causes a second wave to travel down the transmitted bar. Common variable-resistance strain-gages mounted in the center of both bars record the elastic strain waves in the bars. The strain gage signals can be used to calculate the stress-strain

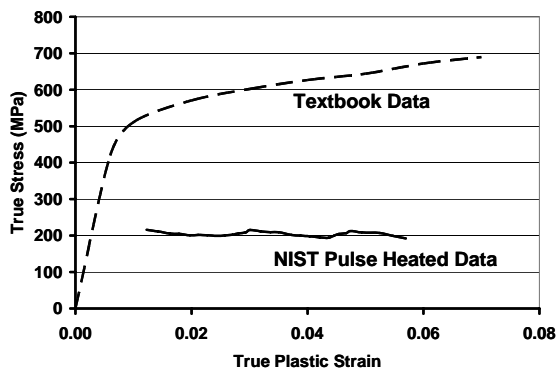


FIGURE 1. Stress-strain curve for aluminum alloy 7075-T6. Upper curve is from Meyers [4] for room temperature conditions and for strain-rates of 0.03 s^{-1} to 560 s^{-1} . The lower curve is NIST pulse heated data for a test temperature of 300°C and strain-rate of approximately 1500 s^{-1} .

curve for the sample material for large plastic strains at high strain rates. The NIST Kolsky bar also has the capability to pulse heat the sample prior to the impact test and produce a stress-strain curve for the sample material at an elevated temperature. Details of the NIST Pulse Heated Kolsky bar are described by Basak [3]. An example of data obtained for an aluminum alloy is presented in Fig. 1.

EXAMPLE CALCULATION

For the example problem discussed above, the cutting forces can be estimated by assuming:

- the width of the cut is 0.5 mm;
- the depth of the cut (feed per revolution) is a practical minimum of about five times the edge radius (sharpness) of the tool, so we could assume a minimum of about 0.050 mm for a high speed steel tool (less for a diamond tool);
- the tool is designed to minimize normal cutting forces, or the tool rake is about 10° ;
- the temperature in the shear zone is assumed to be elevated, in the range of 300°C .

Then the compression flow stress is about 200 MPa (from Fig. 1, lower curve, assuming perfectly plastic behavior), making the shear flow stress about 100 MPa (shear stress is half the normal stress assuming pure compression and using the common Mohr's circle relationship.) The cutting force is then calculated from formula (4) to be: $F_C \approx 5.0 \text{ N}$. And, the thrust force would be: $F_T \approx \pm 0.5 \text{ N}$ from the assumption discussed above that the thrust force would be an order of magnitude smaller than the cutting force if the tool rake angle was adjusted to minimize the thrust force.

The part will deflect away from the tool (or pulled to the tool) with the thrust force, making the part tapered. The amount of this deflection, x , can be estimated with a simple cantilever beam deflection equation when the thrust force is known

$$x = \frac{1}{3} \cdot \frac{F_T \cdot L^3}{E \cdot I} \quad (5)$$

where F_T is the thrust force ($\approx 0.5 \text{ N}$), L is the length of the part ($= 100 \text{ mm}$), E is the modulus of elasticity ($= 70 \text{ GPa}$), I is the area moment of inertia of the tube, $I = \frac{1}{4} \cdot \pi \cdot (R_o^4 - R_i^4)$, where R_o

and R_i are the outer and inner radii of the tube cross section. To make this part with process-induced errors approximately the same as the

machine-induced errors, we should limit the deflection, x , to approximately the same as the machine tool-induced errors, or let us assume about $1\ \mu\text{m}$. We can now calculate the outer radius, R_0 , for this maximum deflection using equation (5) with $R_i = 10\ \text{mm}$. From this calculation, $R_0 \approx 10.7\ \text{mm}$, so the wall thickness would be about $0.7\ \text{mm}$.

DISCUSSION AND CONCLUSIONS

Although the calculations illustrated here are very approximate, we have provided an approach and a quantitative estimate of how thin a wall (approximately $0.7\ \text{mm}$) could be turned on an aluminum cylindrical tube of $100\ \text{mm}$ length and $20\ \text{mm}$ inside diameter. The tool has been designed to limit the effect of cutting forces on part geometry rather than to maximize the material removal rate. To further optimize the process for precision, the tool radius and feed rate will need to be adjusted to ensure the surface finish is the best obtainable for a particular machine tool.

By using a diamond tool, we could possibly decrease the depth of cut and thereby decrease the cutting and thrust forces. Therefore, an even thinner wall would appear possible with a diamond tool. However, dynamic concerns such as chatter would have to be considered when the wall thickness becomes thin.

From experience we would have to address other contributions to the error budget, such as flattening of the shell, for a complete analysis of the process for making this thin-walled part. Thermal effects causing shape and size changes in the tube must also be included in a complete error budget.

In analyzing a process to determine cutting forces as presented here, it is necessary to have a flow shear stress value for the work piece material. A more detailed process analysis, such as the use of the FEM method, can provide more exact values of cutting forces and details such as cutting temperatures. However, an even more complete material description, such as a constitutive material model based on data obtained from a series of pulse heated Kolsky bar tests, is required by the FEM method.

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