MODEL DEVELOPMENT FOR CUTTING OPTIMIZATION IN HIGH-PERFORMANCE TITANIUM MACHINING

MAKINO

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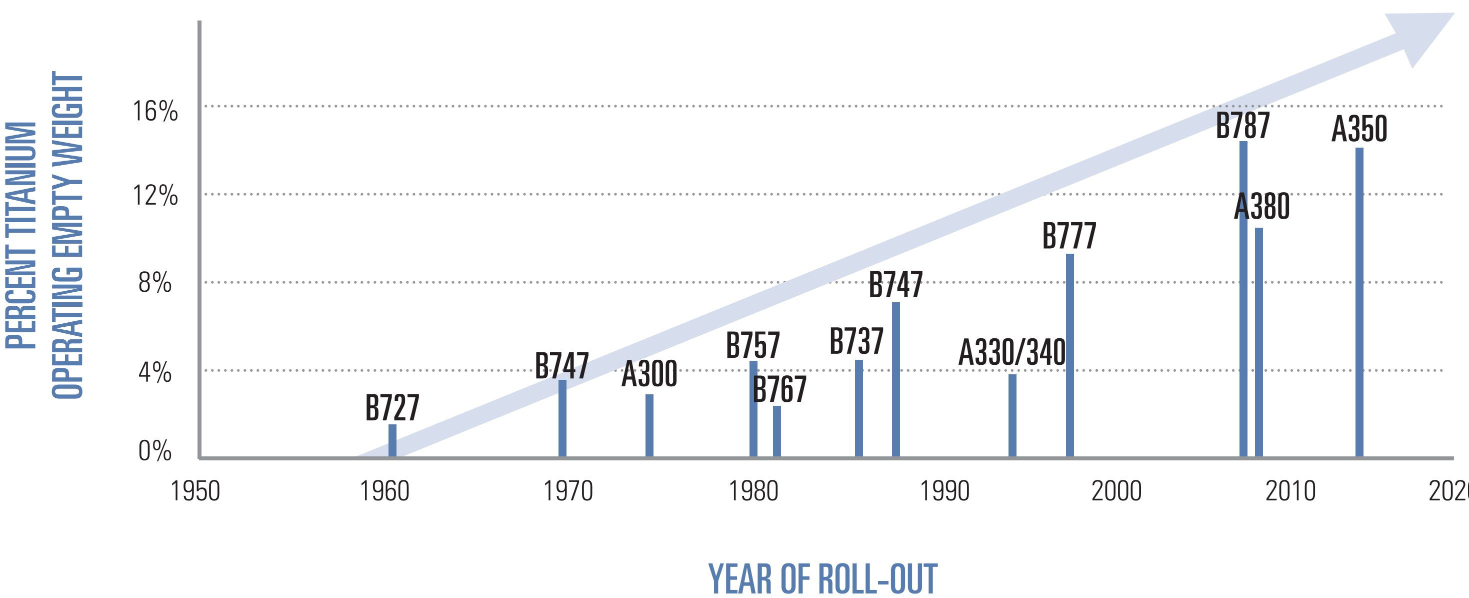
DESIGN APPLICATIONS OF TITANIUM ALLOYS

Titanium alloys have been widely used in the aerospace, biomedical and petroleum industries due to their good strength-to-weight ratio and superior corrosion resistance. Critical applications requiring the ultimate in weight-optimized designs or applications that see the most extreme environmental conditions are ideal for the use of titanium. As designers look to further improve their designs and as modeling technologies advance, industries are turning to titanium more often than ever.

The benefits of titanium come at a price, however. Where aluminum can be cut at rotational speeds exceeding 30,000 rpm with high feed rates and significant depth of cut, the inherent strength of titanium alloys causes increased cutting forces and poor machinability. Its low thermal conductivity creates elevated cutting temperatures concentrated at the tool/chip interface. Coupled with the fact that titanium has high chemical reactivity at elevated temperatures, the result is significant tool wear and cutting speeds on an order of magnitude lower than other structural metals.

PERCENTAGE OF TITANIUM USED IN AIRPLANE DESIGNS SINCE 1950

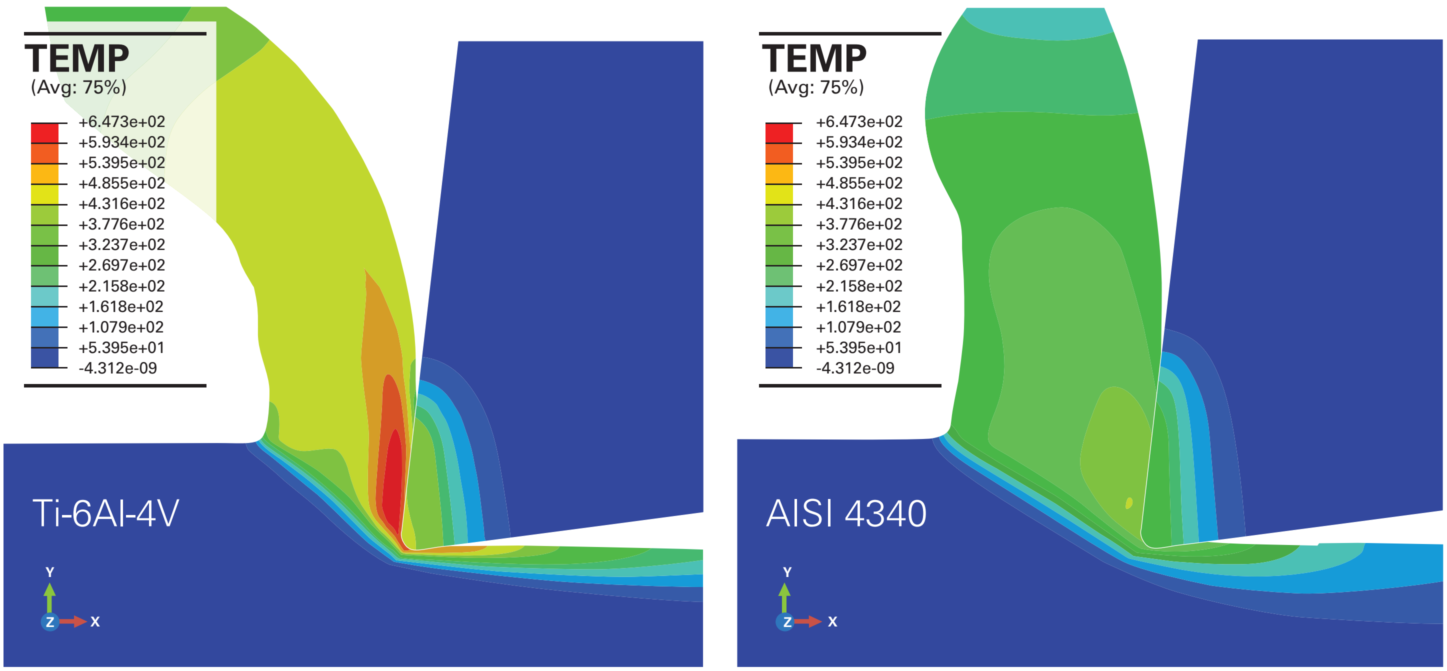


The increasing use of titanium magnifies the need for understanding and optimizing high-performance titanium machining.

CUTTING TEMPERATURE IS CRITICAL

As an example of the complications that arise in machining titanium alloys, the following simulated cutting temperatures were captured during dry cutting Ti-6Al-4V and AISI 4340 with the same cutter, with a cutting speed of 60 m/min and 0.2 mm axial depth of cut.

CUTTING TEMPERATURE COMPARISON: TI6AL4V VS. AISI 4340



Maximum cutting temperature in titanium was 200°C (392°F) higher than that of steel under the same cutting conditions.

The thermal conductivity of Ti64 is 15 percent of that for AISI 4340, resulting in dramatically increased heat concentration. For Ti64, the temperature at the tool/chip interface reaches more than 600°C (1112°F); however, for 4340, the highest cutting temperature is 200°C (392°F) lower.

Compounding the thermal issue, the increased strength of the titanium alloy also results in a thinner chip and shorter tool/chip contact length. The net result is more thermal energy to be dissipated in a smaller volume of material that is inherently less able to conduct heat. This observation clearly highlights why controlling cutting temperature is the most challenging problem in high-performance titanium machining.

YIELD STRENGTH OF TOOL AND WORK MATERIALS

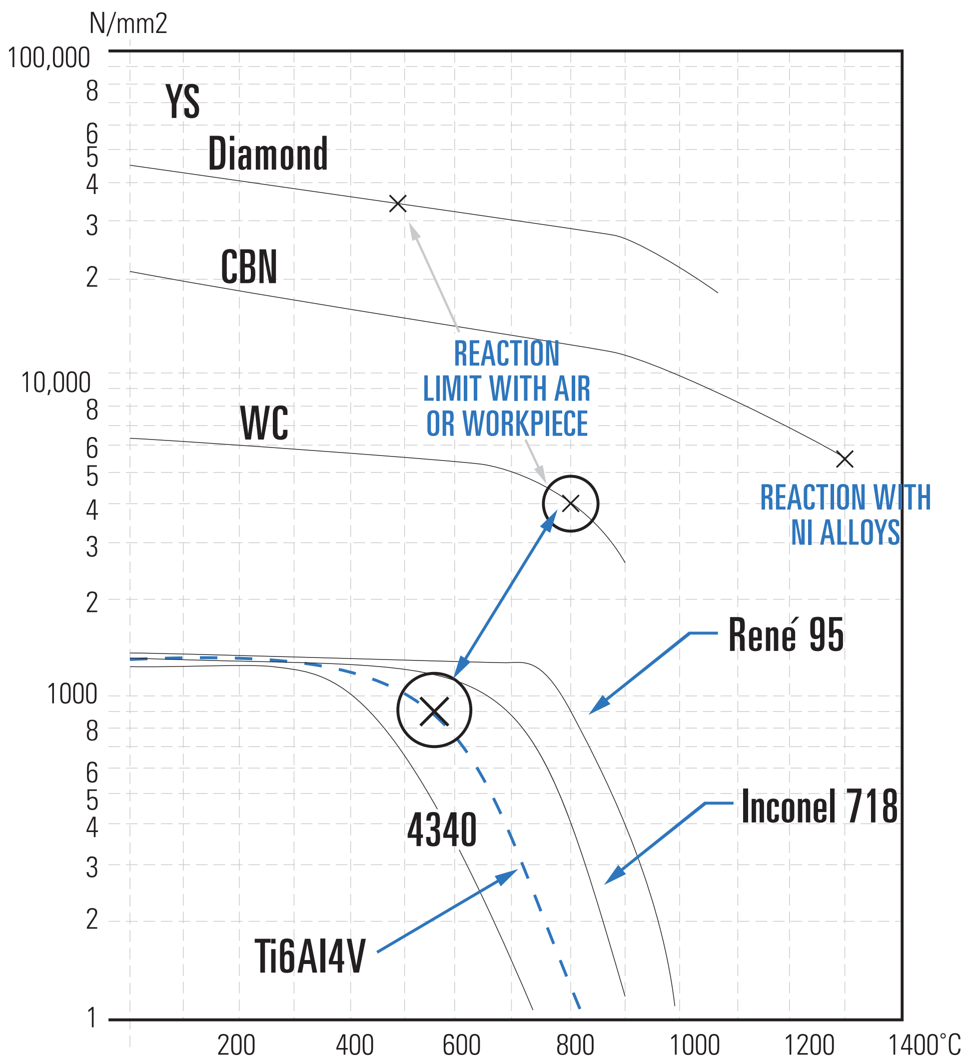
The importance of cutting temperatures can be seen by looking at the characteristic plots of material yield strength against temperature for both the cutting tool and workpiece.

Clearly, a material's yield strength is reduced as temperature increases. In terms of the workpiece, this is useful information in that increased temperature makes it easier to remove material. The critical factor, however, is the impact on the mechanical strength of the cutting tool material.

As seen in the graph, once tungsten carbide (WC) reaches 800°C (1472°F), its mechanical strength is sharply reduced. This temperature is called the reaction temperature and it differs by material. This reduction in strength limits the cutting temperature of WC to about 800°C, whereas cubic boron nitride (CBN), by comparison, can handle 1200°C (2192°F). Thus, an ideal temperature exists for maximizing productivity that softens the work material while maintaining mechanical strength of the tool.

Determining this critical temperature is key to high-performance titanium machining.

YIELD STRENGTH OF MATERIALS VS. TEMPERATURE

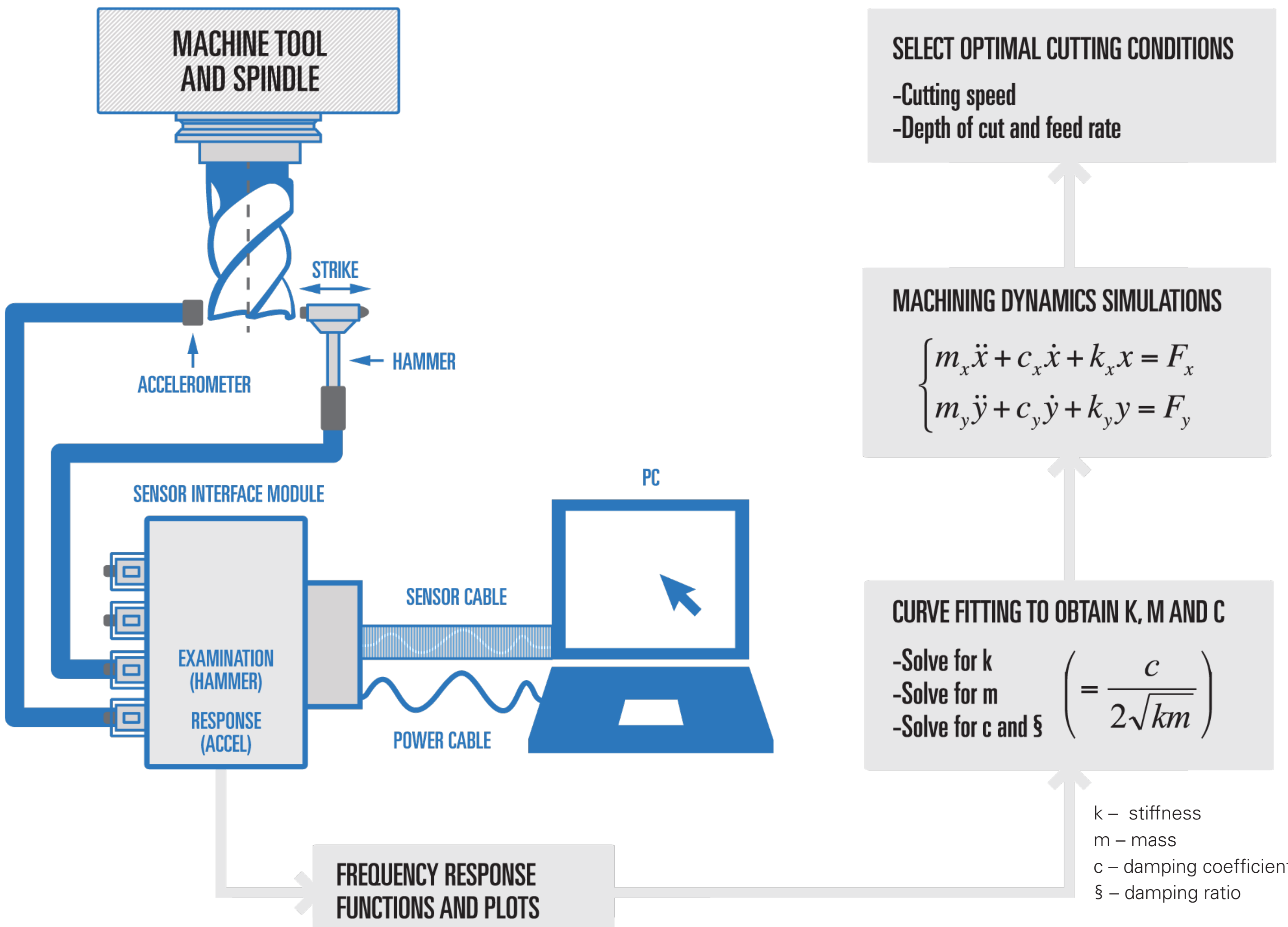


The key factor in titanium machining is keeping temperatures where the material is easier to remove while maintaining tool integrity.

THE CONVENTIONAL METHOD FOR SELECTING CUTTING CONDITIONS

Tap testing is widely used in aluminum machining to determine the cutting conditions to be used for a particular machine/holder/tool combination.

TYPICAL PROCESS FOR TAP-TEST DETERMINATION OF OPTIMAL CUTTING CONDITIONS



Tap-test data is used to generate frequency response plots for the system and the calculation of cutting forces that allows selection of the optimal cutting speed, depth of cut and feed rate.

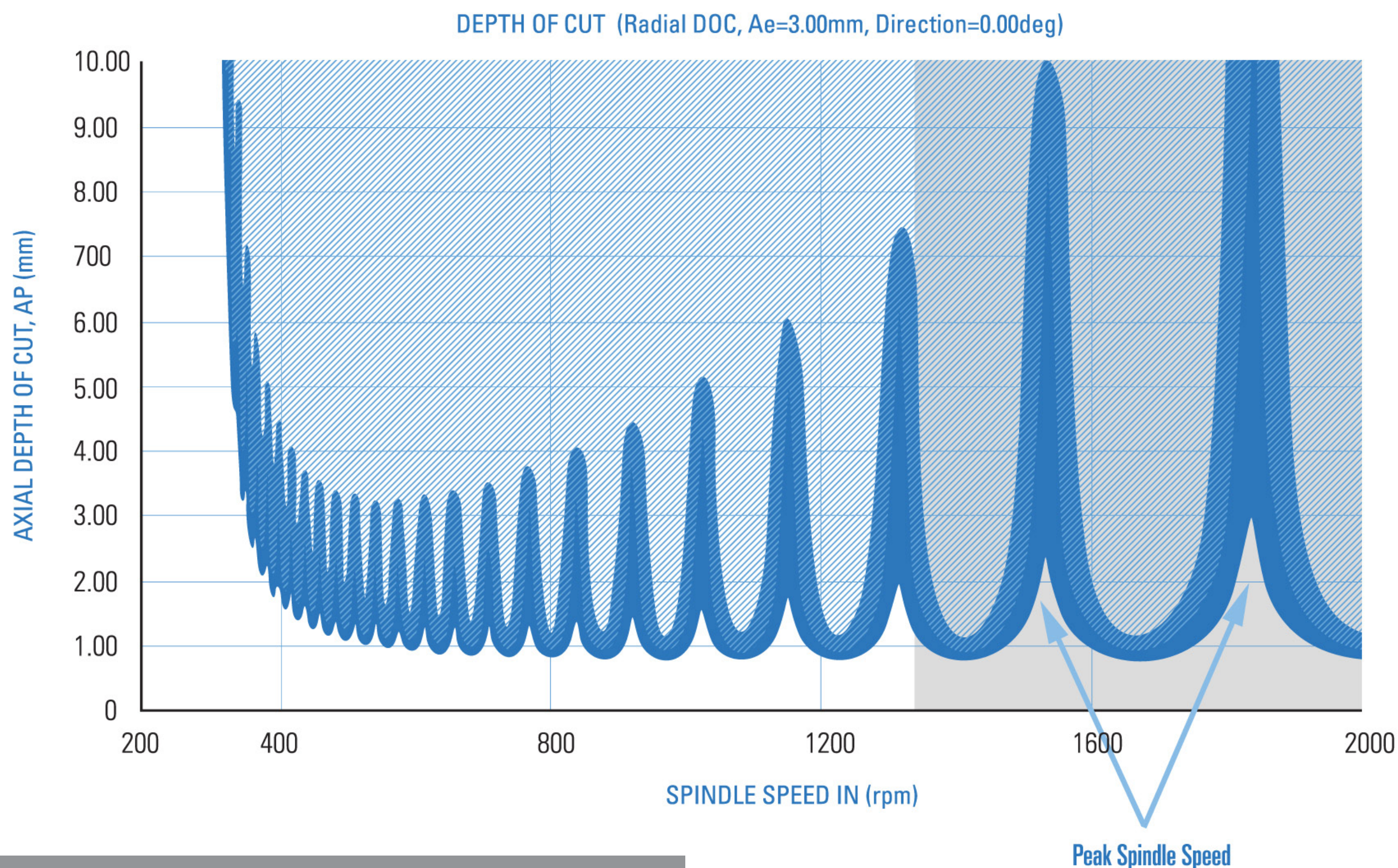
An accelerometer is mounted to the tool in the machine, and an instrumented hammer is used to tap the tool. The hammer provides the excitation input while the accelerometer records the resulting response of the machine/tool system. The data is analyzed with software that determines the natural frequency response of the entire cutting system.

The frequency response is used in curve fitting to obtain constants k, m, c and § that are used in a machining dynamics simulation that calculates the corresponding cutting speed, depth of cut and feed rate.

STABILITY LOBES IN TITANIUM MACHINING

The frequency response and force information from the tap test generates a plot of stable combinations of axial depth of cut and spindle speed. In general, high spindle speeds are preferable for high material-removal rates; however, they cause sharp increases in cutting temperature that must be reconciled with the tool material limits.

TAP-TEST ANALYSIS RESULTS FOR DEPTH OF CUT VS. SPINDLE SPEED

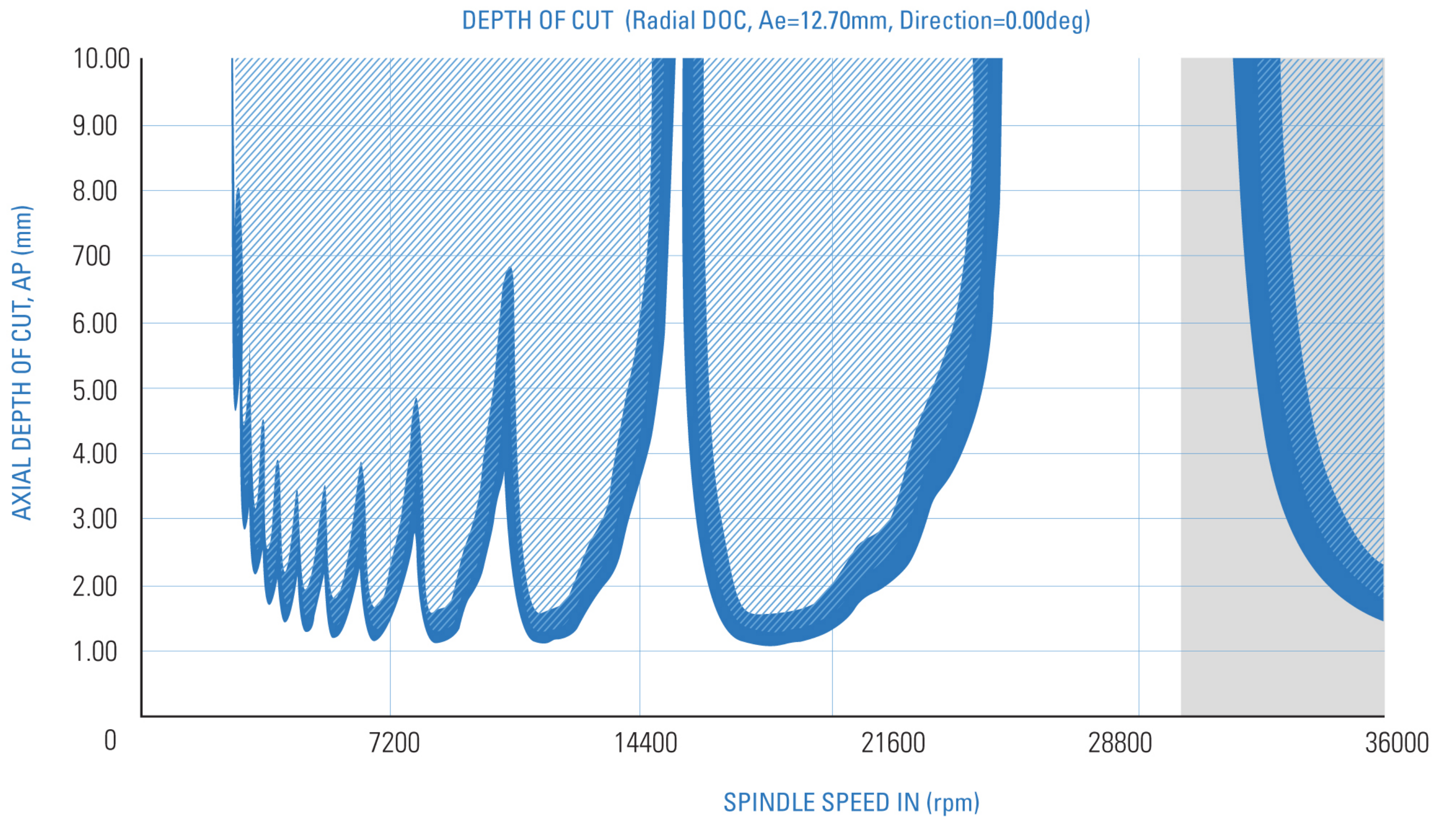


Unstable combinations due to vibration are in the blue area, whereas those in the gray area result in too much heat in the part and/or tool.

These plots feature "stability lobes" above which the combination of depth of cut and spindle speed results in unacceptable vibration. In the plot above, the blue areas are unstable combinations that would cause too much vibration. The gray areas indicate that conditions are too fast and would generate too much heat. At a basic level, the key is to select the highest speed that falls under the last acceptable lobe to give the largest possible depth of cut.

Reality prevails, however, and an additional consideration is the range that must be maintained at the selected speed. Choosing a combination without a large enough speed range around it can cause instability. This scenario is another challenge for machining titanium, because the relative widths of the lobes in these plots for titanium are considerably narrower than in other materials.

STABILITY LOBES FOR MACHINING OF ALUMINUM ALLOY WITH FIVE-FLUTE, 0.5-INCH CARBIDE TOOLS



For example, a plot in aluminum would have a stable range that might reach out to 30,000 rpm, providing a much wider set of stability lobes and less precise requirements on spindle speed throughout the cut. Titanium demands much finer control to maintain the “sweet spot” at the peak of the optimal stability lobe for maximum productivity.

OBJECTIVES AND APPROACHES

Makino undertook an effort to systematically study heat generation in high-performance machining of titanium alloys to develop a deep understanding of the interaction of the influences involved. With that knowledge in hand, processes and theoretical models were developed for selecting optimized cutting conditions and efficient cooling strategies.

Goals for this work:

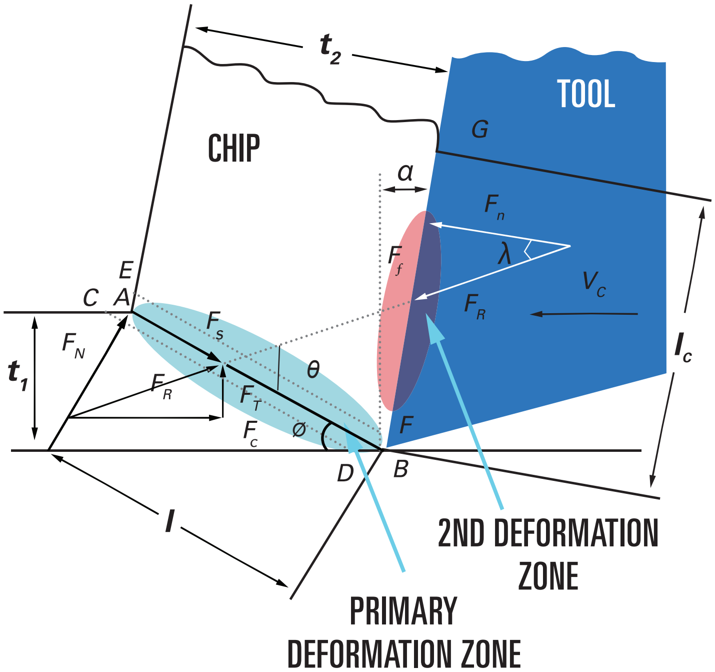
- Maximum titanium machining productivity
- Longest tool life
- Best finished surface quality

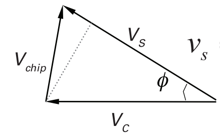
In order to achieve these objectives a process was developed to estimate the cutting forces, shear angle, etc., involved in cutting titanium. This process was then used to model the cutting temperature distribution at the tool/chip interface, which could be used for selection of optimal cutting conditions.

For verification, physical experiments were carried out for comparison to the theoretical model. This procedure was repeated and improved until the calculation error fell within a suitable threshold value to consider the model proven.

MODELING SHEAR AND FRICTIONAL FORCES IN THE DEFORMATION ZONES

During orthogonal cutting, as the tool moves through the material to be removed, there are two regions where heat is generated. The main component to the cutting temperature is heat generated in the primary deformation zone due to plastic work done by the shear force (F_s) in the shear plane. Also significant is the heat generated in the secondary deformation zone due to the friction force (F_f) at the tool/chip interface as the tool pushes the chip away from the workpiece.





$$v_s = \frac{v_C \cos\alpha}{\cos(\phi - \alpha)}$$

$$F_C = \frac{T_m}{r}$$

$$F_R = \frac{F_C}{\cos(\theta - \phi)} = \frac{T_m}{r\cos(\theta - \phi)}$$

$$F_S = F_R \cos\theta = \frac{T_m \cos\theta}{r\cos(\theta - \phi)}$$

$$F_f = F_R \sin\lambda = \frac{T_m \sin\lambda}{r\cos(\theta - \phi)}$$

$$\lambda = \theta - \phi + \alpha$$

where t_1 is undeformed chip thickness, t_2 is chip thickness, l is the length of the shear plane, l_c is the tool-chip contact length, α is the rake angle, Ø is the shear angle, λ is the friction angle at the tool-chip interface, θ is the angle made by the resultant cutting force and shear plane, F_C is the force component in the cutting direction, F_T is the force component vertical to the cutting direction, F_f and F_n are the frictional force and the normal force at tool-chip interface, F_N is the force normal to the shear plane, F_S is the shear force on the shear plane, F_r and F_t are force components in radial and tangential directions, F_R is the resultant cutting force, T_m is the cutting torque, V_C is the cutting speed, V_{chip} and V_S are the chip velocity and shear velocity, respectively.

The forces generated in the two deformation zones must be calculated in order to determine the power needed to complete the cut.

In order to determine the power involved in the cut and thereby be able to estimate the cutting heat generated, it is necessary to know the shear force along the shear plane and friction force at the tool/chip interface.

MODELING OF FLOW STRESSES

Flow stress is defined as the yield stress under uniaxial conditions at which materials start to deform plastically. Many researchers have developed techniques to determine the flow stress of metals. The most widely used is the Johnson-Cook (JC) strength model that represents the flow stress of a material as the product of strain, strain-rate and temperature:

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n][1 + C\ln(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0})][1 - (\frac{T - T_r}{T_m - T_r})^m]$$

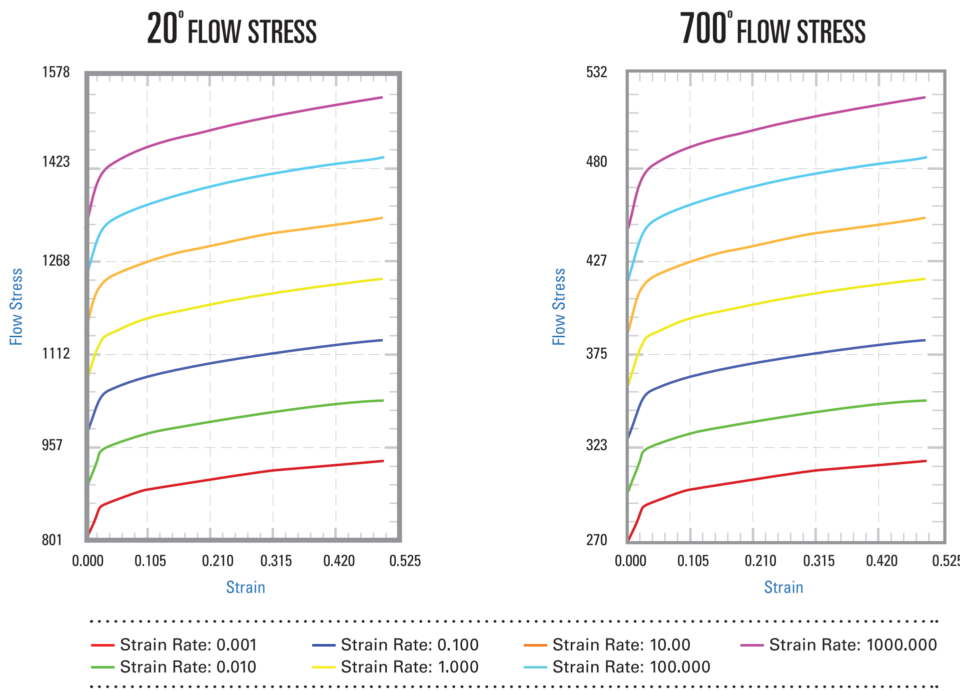
This model shows where A, B, n, C and m are fitted based on existing Hopkinson bar experimental test data with Levenberg-Marquardt modifications for the global convergence method.

Previously published JC data provides the following model of flow stress for Ti64 under 20°C (68°F) and 700°C (1292°F) across a range of strain rates.

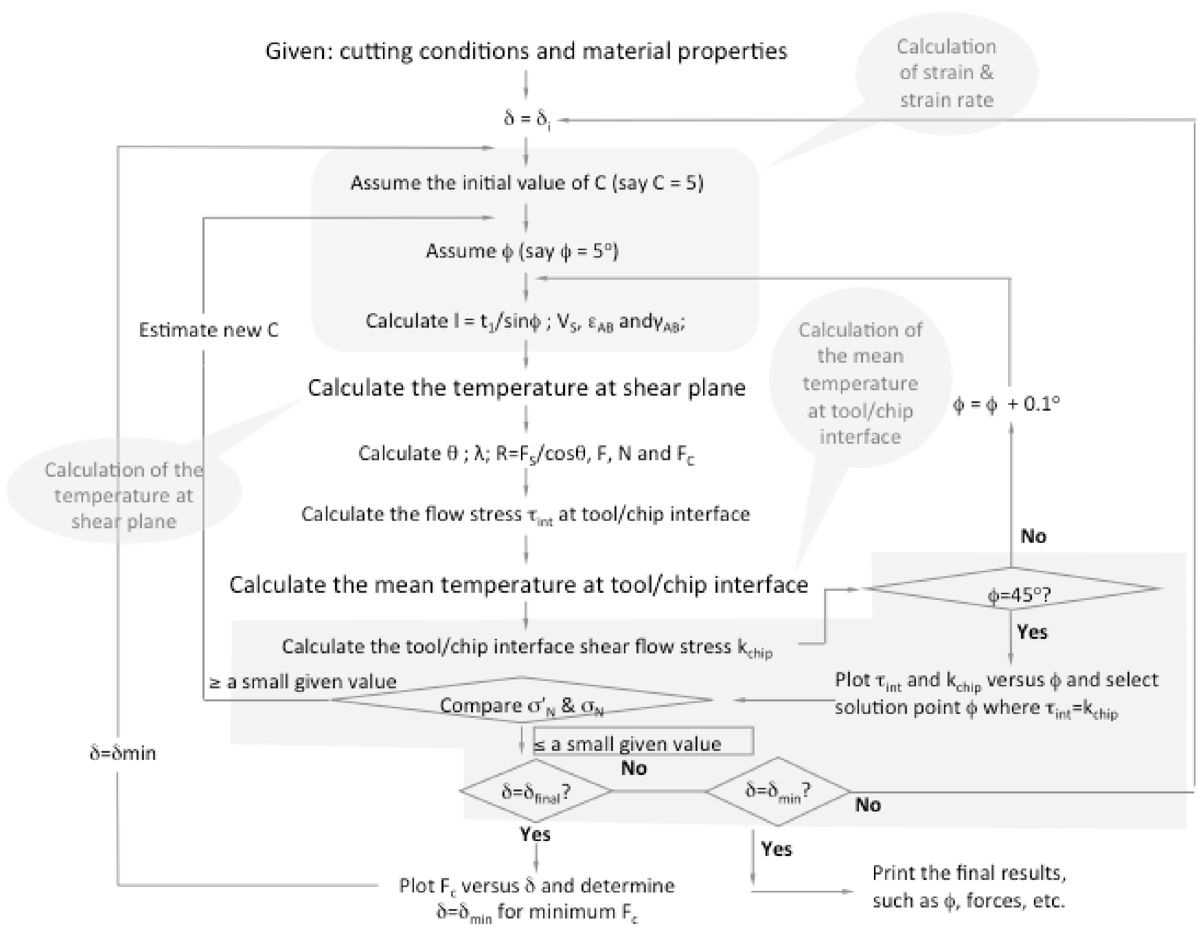
Clearly and as expected, with the increase of the temperature, the flow stress is reduced. Similarly, as the strain rate is decreased, so is the flow stress. Thus, it is easier to remove the material as the work material temperature increases.

Considerably lower flow stresses are seen in Ti64 at 700°C (1292°F) and at lower strain rates.

FLOW STRESS MODELS FOR TI64 AT 20°C (68°F) AND 700°C (1292°F)



MODEL FOR ESTIMATION OF CUTTING FORCES IN TITANIUM MACHINING



Strain, strain rate and cutting temperature at the shear plane and tool/chip interface are calculated, and then flow stress and cutting forces are determined. Equilibrium conditions are checked to ensure compliance before defining the final cutting forces.

MODELING OF CUTTING FORCES

Based on the JC strength model, an analytical cutting force model could be developed. This flowchart shows the cutting force model used in this study.

Four main procedures are involved in the model:

1. Strain and strain rate are calculated.
2. Temperature along the shear plane and the mean temperature at the tool/chip interface are calculated.
3. The JC strength model is used to calculate the flow stress and cutting forces.
4. The equilibrium conditions at the tool/chip interface are checked.

The whole procedure is repeated until all of the equilibrium conditions at the tool/chip interface are met. Once they are, the shear force and frictional force can be obtained.

ESTIMATION OF CUTTING FORCES

In order to estimate the cutting forces involved and eliminate the physical test otherwise used to determine the coefficient, specific cutting pressure (K_c) can be estimated with the following equation:

$$K_C = \frac{k_{AB}\cos(\lambda - \alpha)}{\sin\phi\cos\theta}$$

The equation illustrates that k_{AB} is the flow stress along the shear plane, λ is the friction angle, α is the rake angle, ϕ is the shear angle, and θ is the angle made by the resultant force and the shear plane.

Once K_c is defined, the friction forces at the tool/chip interface can be estimated, and the friction force multiplied by the cutting speed allows the calculation of the cutting power involved.

$$F_f = \frac{K_C t_1 w}{\cos(\lambda - \alpha)}\sin\lambda = \frac{k_{AB} t_1 w}{\sin\phi\cos\theta}\sin\lambda$$

Tool chip contact length is shown as l_c, where C_n is the strain rate constant and n_1 is the strain hardening index.

$$l_c = \frac{t_1\sin\theta}{\cos\lambda\sin\phi}\left\{1 + \frac{C_n n_1}{3[1 + 2(\pi/4 - \phi) - C_n n_1]}\right\}$$

Once the shear and friction forces are known, the shearing power and friction power can be calculated with the two equations above. The shear plane temperature can be calculated based on the assumption that all shearing power is converted into heat.

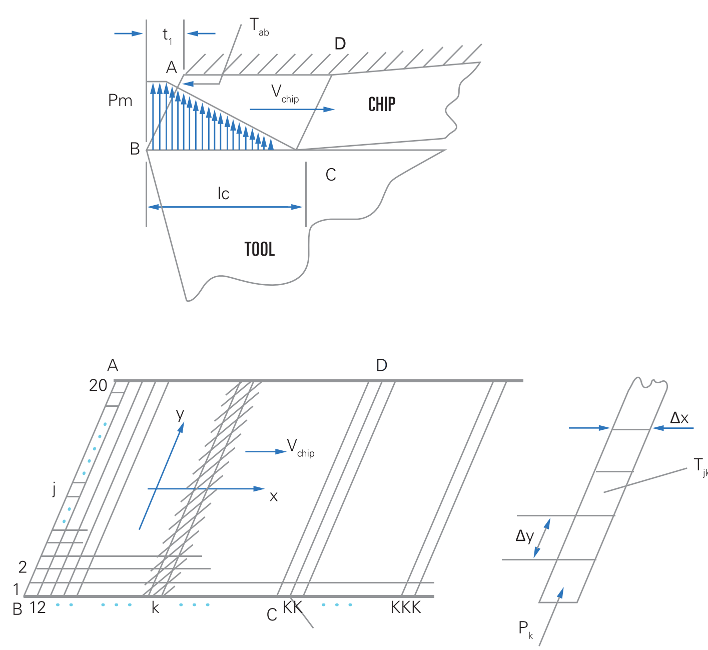
$$T_s - T_r = \frac{F_s v_s}{bhv\rho c} = \frac{K_C\cos\theta}{\cos(\theta - \phi)}\frac{\cos\alpha}{\cos(\phi - \alpha)}\frac{1}{\rho c}$$

In the above equation, c and ρ are the specific heat and density of the work material, respectively. From this equation, we can see that the shear plane temperature (T_s) does not depend on the chip dimensions such as width of cut and undeformed chip thickness, nor is it directly contingent on the cutting speed. Shear temperature is determined by the mechanical and thermal properties of work materials, rake angle and shear angle, which indirectly depends on cutting speed and undeformed chip thickness.

CUTTING-TEMPERATURE CALCULATION

Using the following friction model, the friction power at the interface can be estimated.

MODEL FOR CALCULATING FRICTION POWER



Using this model, the friction power at the tool/chip interface can be calculated for use in determining the cutting temperature.

Temperature in the chip is calculated using a finite difference computation approach.

The entire field of the chip is divided into incremental slices in both X and Y directions. Assuming that the temperature is constant across each element and changes discretely from one element to the next, the method of finite differences can be applied to the field.

$$\left(\frac{T_{j-1,k}-T_{j,k}}{\Delta y}-\frac{T_{j,k}-T_{j+1,k}}{\Delta y}\right)\Delta xbk = b\Delta x\Delta y\rho c\,\frac{T_{j,k+1}-T_{j,k}}{\Delta t}$$

In the computation, both mass transfer and heat conduction are considered in the X direction, and heat conduction is considered in the Y direction. Over the contact length, from 1 to KK, heat input p_k is obtained at its lower end, and the heat spreads in the slice in the Y direction by conduction as well as being conducted away through the tool.

Using this computation, the average temperature (T_{ave}) at the tool/chip interface can be determined, and, with T_{ave} as an input, the power passing through the tool can be found as well. The power passing through the tool is then corrected for the next iteration.

IN-PROCESS CUTTING-CONDITION OPTIMIZATION

After developing the model for the cutting forces and cutting heat generation, the outputs can be used to evaluate the cutting conditions in the process. Based on the input data, such as cutting parameters and tool geometries, along with the in-process monitoring of spindle load and cutting power, the cutting forces and temperatures are continuously calculated using the developed model.

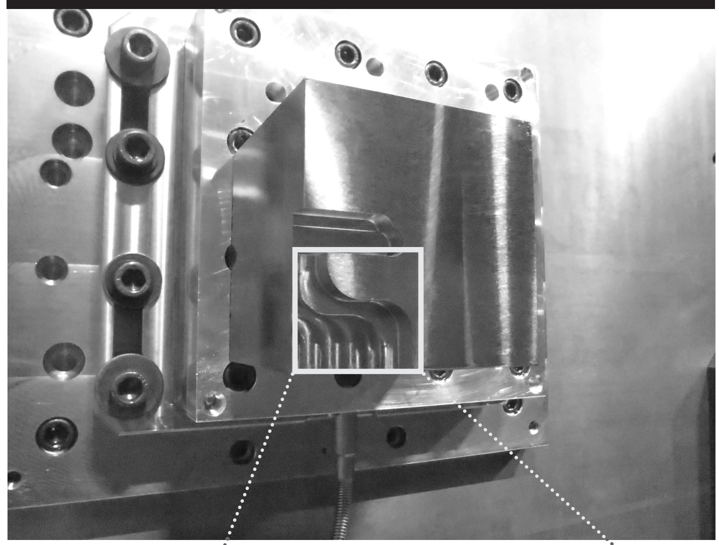
For each calculation, if the resulting error is within the given threshold value, the calculated temperature at the tool/chip interface is checked against the tool material reaction temperature (800°C/1472°F for WC).

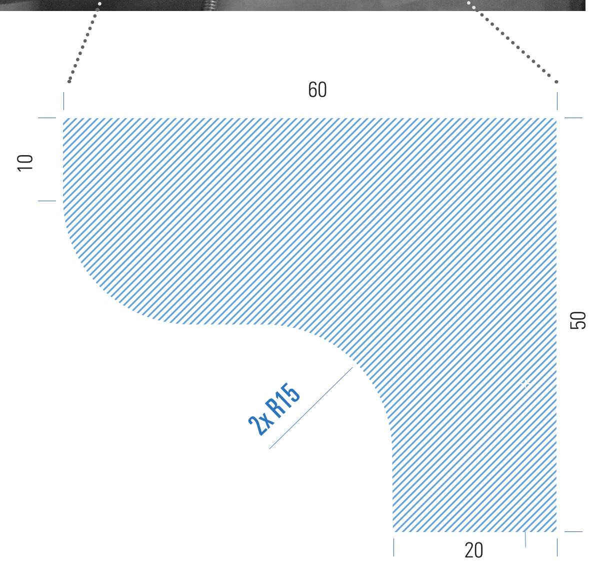
If the error is not within the threshold, the cutting conditions are updated until the highest temperature is less than the reaction temperature for WC-Co materials. Afterward, the cutting process is optimized to achieve minimum cutting power/forces.

VERIFICATION AND CUTTING-FORCE TESTING

In order to test the model results, a series of tests were performed on a titanium workpiece using a cutting path with concave, convex and straight features. This toolpath enabled comparison using three different cutting loads in one pass to truly test accuracy of the model.

EXPERIMENTAL SETUP AND CUTTING-PATH DETAIL





Using a cutting path with concave, convex and straight portions allowed more rigorous verification of the model in one setup with varying cutting conditions.

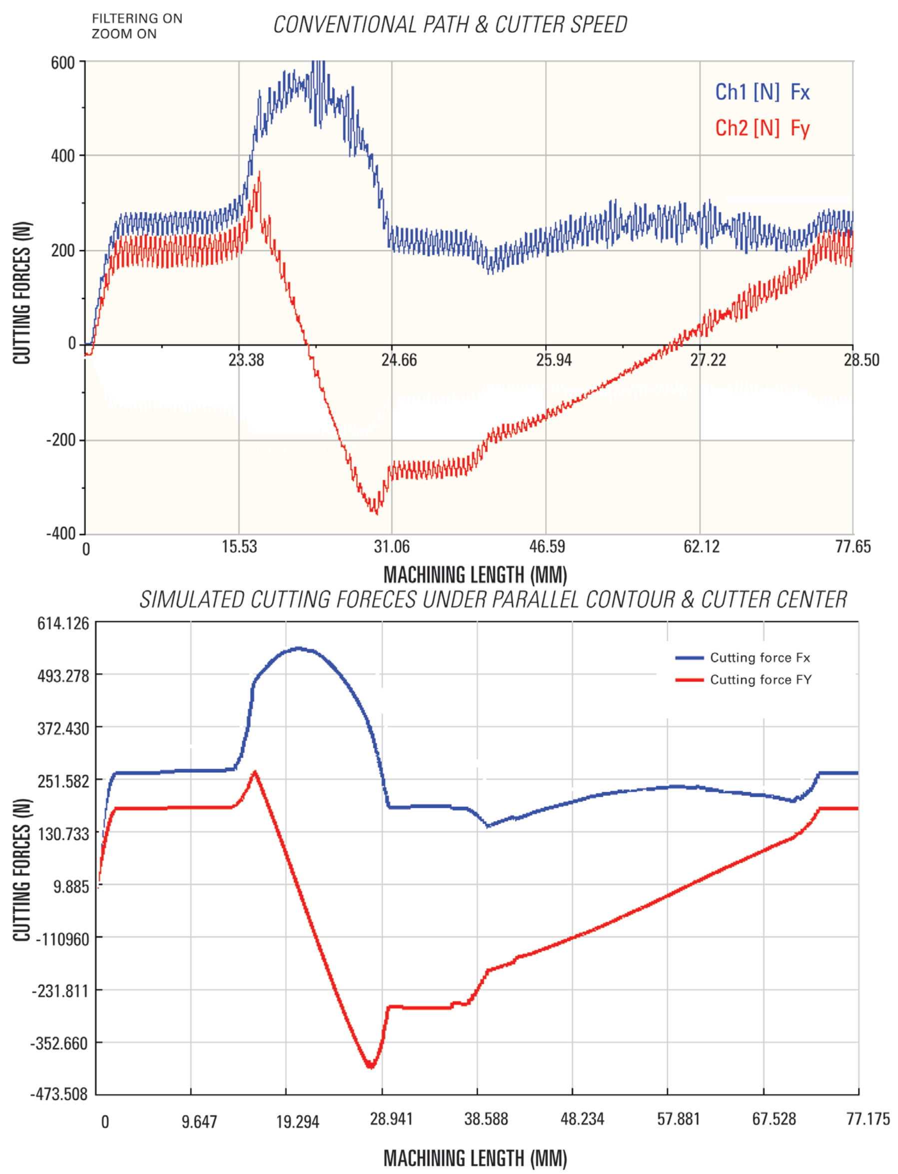
The concave portion of the path has more radial tool engagement and thicker chips, while the convex portion has thinner chips with less engagement, and the straight portion obviously falls between these. A five-flute, 0.5-inch end mill was chosen as the tool for all of the testing.

Cutting conditions for the test cuts:

- Feed rate – f_z = 0.1 mm/r-z
- Cutting speed – V_c = 58. m/min
- Radial depth of cut – a_e = 0.6 mm
- Axial depth of cut – a_p = 12.7 mm

Excellent correlation was seen in all phases of the cut.

MEASURED VS. ESTIMATED CUTTING FORCES



Excellent correlation was seen between the measured cutting forces for the test path. From left to right, the path was straight, concave, straight and convex.

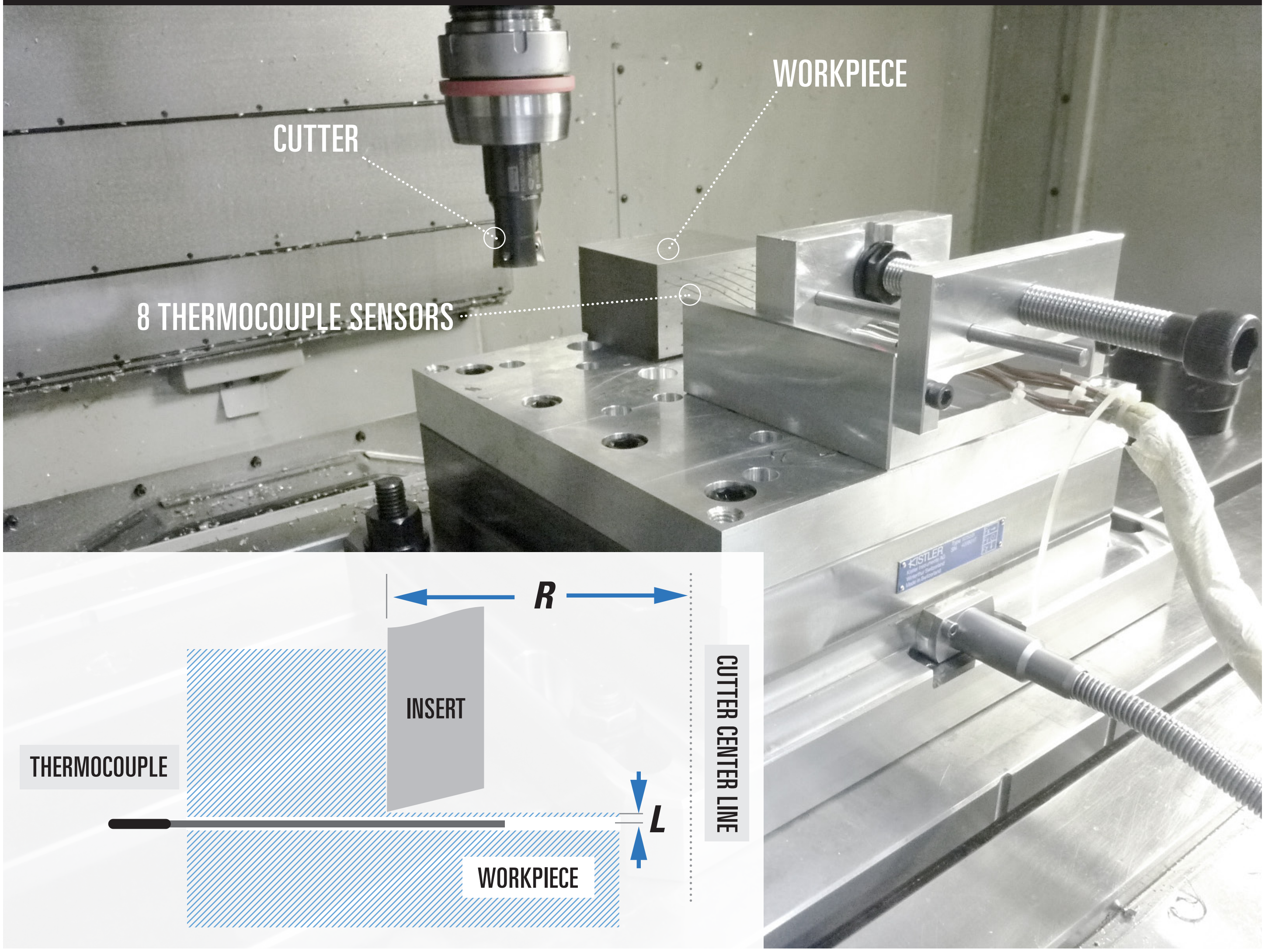
VERIFICATION AND CUTTING-TEMPERATURE TESTING

In order to verify the cutting-temperature model, an instrumented test setup was created to secure a workpiece for running repeated test cuts while measuring temperature in the work zone.

Eight 0.5-mm-diameter thermocouples were placed in the workpiece inside holes drilled 0.4 mm below and parallel to the cutting plane to measure temperature in the work zone throughout the entire length of the test cuts. The same five-flute, 0.5-inch end mill was used in the temperature testing.

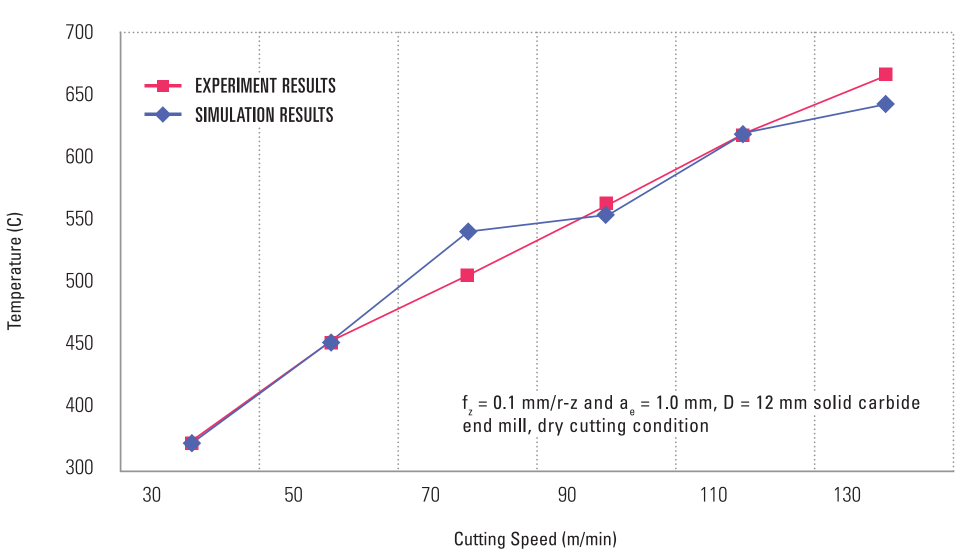
Cutting forces were measured via an instrumented mount, and all data was fed to a PC for comparison against the estimated values developed in the model.

INSTRUMENTED TESTING SETUP FOR TEMPERATURE MEASUREMENT



Eight 0.5-mm-diameter thermocouples were placed in holes 0.4 mm below the cutting plane to measure temperature during the cuts.

MEASURED VS. ESTIMATED CUTTING TEMPERATURES



The modeled cutting temperatures closely matched the actual test data.

As discussed previously, in practical experience, the most significant factor in the cutting temperature of titanium is the cutting speed; therefore, the first and most important comparison performed to evaluate the model against the experimental data was cutting temperature versus cutting speed.

Cutting conditions for the test cuts:

- Feed rate – f_z = 0.1 mm/r-z
- Radial depth of cut – a_e = 1.0 mm

As can be seen here, the proposed cutting temperature calculation model predicts cutting temperature with good accuracy.

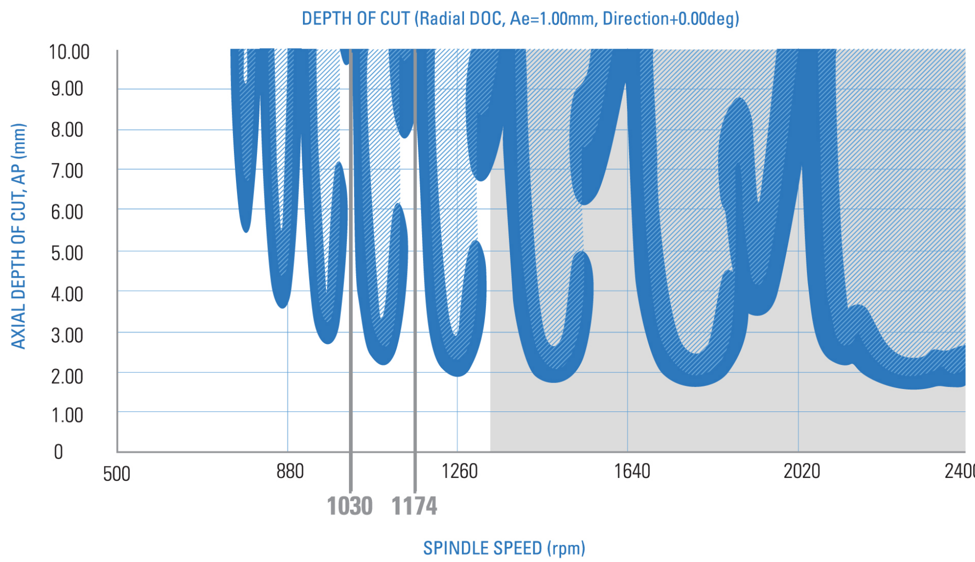
PHYSICAL TAP-TEST RESULT

Once the temperature predictions were seen to be accurately tracking the physical test-cut data, physical tests were performed to optimize the cutting process.

For the test setup used in the temperature measurement experiment, tap tests were performed to identify the stable rotational speeds that were indicated as the most productive, with the greatest possible depth of cut.

In these results, the highest speeds that remained in the stable cutting range and under the characteristic temperature of WC were 1,030 and 1,174 rpm. These speeds were used to verify the results and optimization process through physical experimentation.

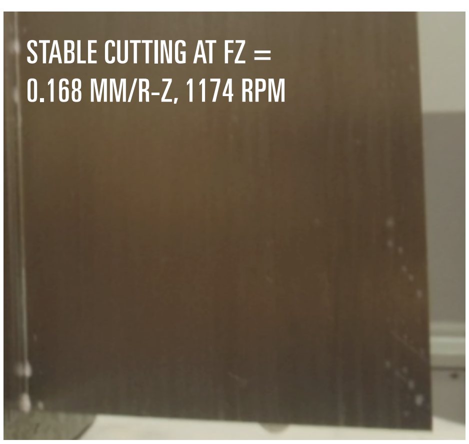
STABILITY LOBE PLOT OF DEPTH OF CUT VS. SPINDLE SPEED



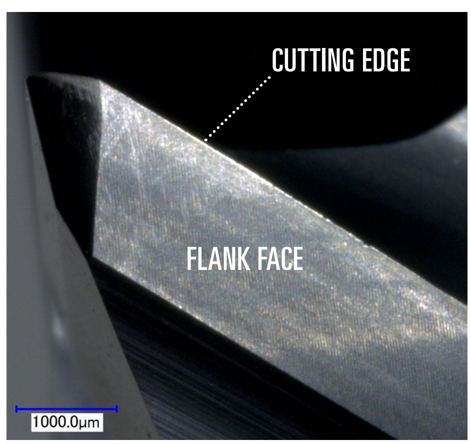
Using tap-test analysis, the highest stable spindle speeds were selected at 1030 and 1174 rpm, and then used to optimize the cutting process.

PHYSICAL EXPERIMENTAL VERIFICATION

EXPERIMENTAL RESULTS OF OPTIMIZED TEST CUTS



Machined surface profile at 1174 rpm



Tool flank after 16 passes

Test cuts were conducted at 1,174 rpm to check surface finish and tool wear under actual cutting conditions to ensure that the cutting process remained stable and the temperatures were below the critical temperature for extended tool life in the WC cutter.

During testing, the average temperature at the tool/chip interface reached 650°C (1202°F), below the 800°C (1472°F) critical temperature threshold, and the flank tool wear was less than 0.1 mm after 16 passes.

CONCLUSIONS

- An analytical cutting-force model for milling processes in Ti64 has been developed that provides good accuracy in predicting the cutting forces when compared to experimental cutting data.

- Numerical simulation was performed to estimate the temperature distribution at the tool/chip interface. Cutting speeds and radial depth of cut have more dominant effects on cutting temperatures than do feed rates.

- Average cutting temperature at the tool/chip interface was measured in experimental testing and was found to be controlled within the characteristic temperature of WC material to maintain reasonable tool life in a stable finishing operation optimized to achieve high productivity as well as long tool life.

- Physical experimentation has verified that the proposed theoretical modeling approach can achieve high-performance machining of titanium alloys.

RESOURCES

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A New Approach to Titanium Machining

Integral Changes Increase Productivity at Davis Tool

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