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HIGH SPEED CUTTING OF SUPERALLOYS

A possibility to improve the productivity in production industry is the implementation of high speed cutting processes. In particular, the high performance machining of superalloys such as titanium- and nickel-based alloys makes high demands on tools and machines. Therefore, it is important to understand the chip formation mechanisms during high speed cutting.
This paper describes the effect of different influential variables including the tool chip angle, cutting velocity, chip thickness and the structure of the superalloys Inconel 718 and TiAl6V4 on chip formation and cutting forces. The experiments were accomplished on a a quick-stop experimental rig, which allows to decelerate the workpiece, even for very high cutting speeds, within a distance which is smaller than the chip thickness.
The experimental examinations were completed by temperature measurements. The knowledge of the resulting tool, workpiece and chip temperatures from high performance machining of hard machinable alloys at high cutting speeds contributes to understanding of the different chip formation mechanisms and the influence on tool-life.

1. INTRODUCTION

Superalloys like titanium- and nickel-based alloys show high heat resistance combined with high strength as well as good corrosion resistance. Therefore, superalloys are used when there are extremely high loads on the components. Application areas are for example turbo jet engines in civil and military aviation. There occur very high centrifugal forces and vibrations as well as high temperatures in an aggressive environment. In this field, nickel-based alloys are used for example for highly loaded parts, injectors and blades [1].

Their particular mechanical and physical material characteristics, in combination with the requirements for high component quality and process safety, make the geometrically defined machining of nickel-based alloys a challenging task, even under conventional process conditions [1]. What complicates matters further is the demand for a steadily growing productivity, which could be primarily achieved by a continuous increase of the cutting parameters up to the point of high speed cutting (HSC). However, complicated

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interactions between the forming velocities, the structure and of the material as well as the temperature at the cutting area need to be considered. Those interactions differ considerably from those under conventional process conditions and lead to modified machining and chip formation mechanisms [2]. The range of the cutting velocity for HSC largely depends on the material that is to be machined. The mechanisms for high speed cutting of highly heat resisting alloys have previously been insufficiently explored [3,4].

This paper describes the examination of TiAl6V4 and Inconel 718 at very high cutting speeds. The intention was to identify the different mechanisms on plastic strain, material separation and deflection. Therefore, cutting forces, temperatures, chip formation and shapes of the chip were considered.

2. EXPERIMENTAL SETUP

Fig. 1 shows the test bench used. It is based on a reconstructed grinding machine. Instead of a grinding wheel a disk rotates with two workpieces. The workpieces have a tooth profile that interferes with the disk and copes with the centrifugal forces safely at cutting speeds of more than 100 m/s. They are brought into contact with the cutting edge by radial infeed. The kinematics correspond to that of plunge turning with discontinuous cutting. Machining is accomplished by orthogonal cutting. The cutting conditions remain constant over a cutting length of 50 mm. After a defined number of cuts the cutting edge has to be removed within a short period of time. Therefore, a special retraction device was constructed and produced (Fig. 1, right). The forces occurring in the machining process were recorded by a piezo-force measuring element.

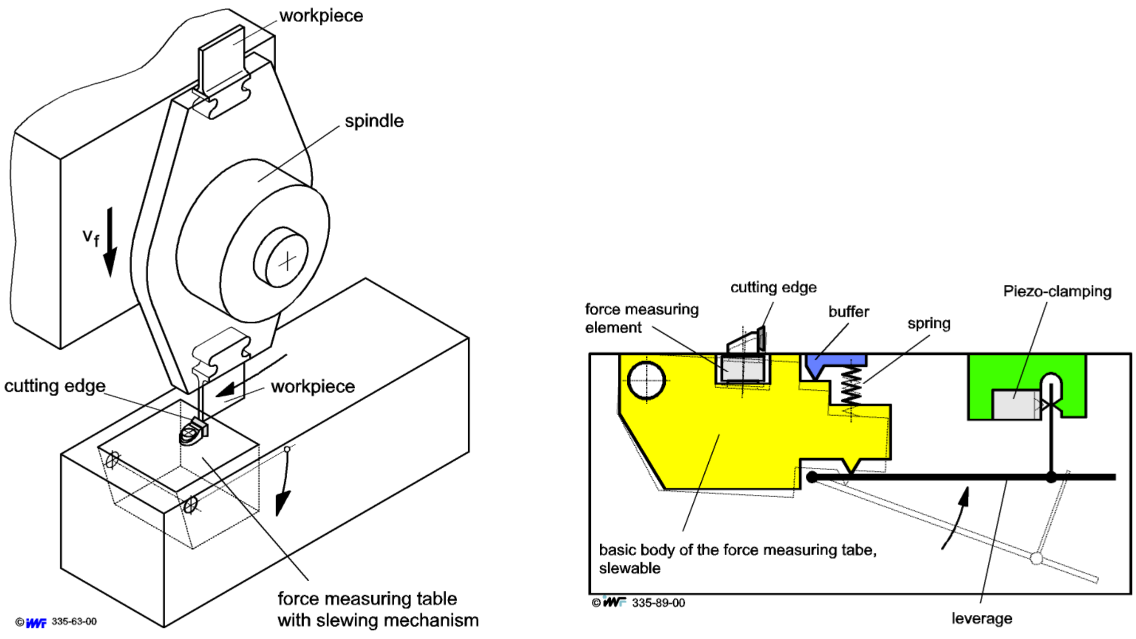


Fig. 1. Test bench (left) and tool retraction device (right)

In order to determine the temperature at the cutting edge during the cutting process, the cutting edge cross section was measured in some experiments with a thermo-camera (Fig. 2). Therefore, the cutting edge was abraded at the front side so that it ended on the same level with the workpiece. Further on, the chip and workpiece temperatures were recorded after a corresponding modification of the experimental setup.

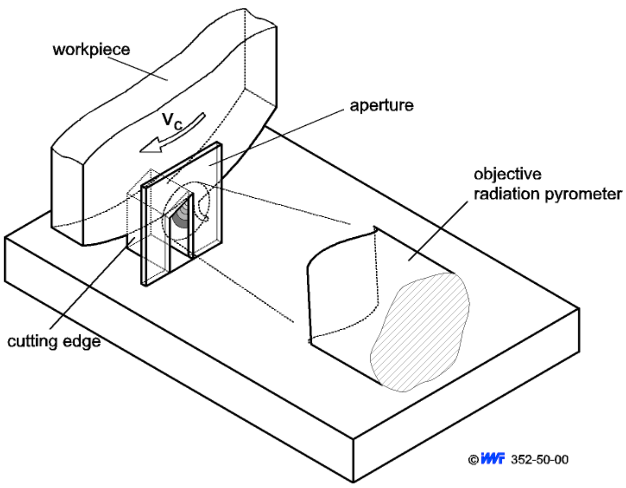


Fig. 2. Arrangement for pyrometric temperature measurements

In order to make further experiments on chip formation, another experimental rig was designed and installed at the IWF. With this quick-stop experimental rig the chip formation process can be „frozen“. In this process, so-called chip roots form, which reflect the single chip formation phases. In order to attain the necessary acceleration for the chip formation, the device works ballistically. In the process, a special workpiece is shot against a baffle plate. The attainable speed is a function of the air pressure and component mass. Immediately before the collision a chip of about 1 mm length is generated. Leaf springs implemented in the device prevent an unintentional return motion of the workpiece. Due to the resulting very short stopping distances a high quality of the formed chip roots is ensured.

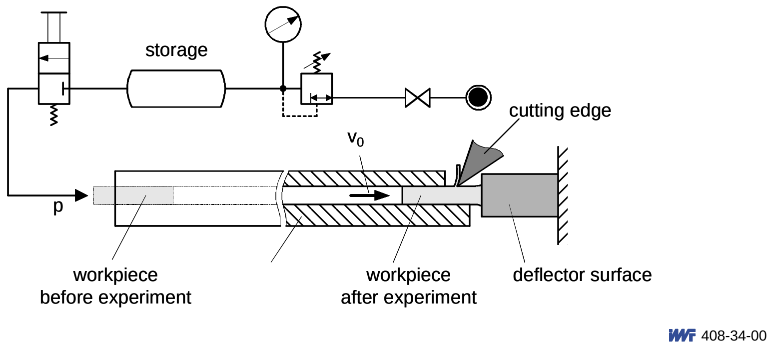


Fig. 3. Quick-stop experimental rig

3. RESULTS

3.1. SPECIFIC CUTTING FORCE AND CHIP FORMATION

During the experiments at the high speed cutting-test bench the cutting force F_c was measured, so that it became possible to calculate the specific cutting force k_c and the stock removal energy. Fig. 4 shows the specific cutting forces for different cutting depth. An increase of the cutting depth from 40 to 80 µm results only in a small proportional rise of the specific cutting force. Otherwise, k_c is almost uninfluenced by the cutting velocity and therefore contradicts the observations of Kienzle, who examined the specific cutting forces for conventional cutting velocities. Using a cutting depth of 15 µm, which lies in the range of the radius of the cutting edge, the influence of the cutting velocity can be clearly observed because the influence of the cutting edge radius cannot be disregarded for this marginal chipping thickness.

If the chip formation of TiAl6V4 is regarded, you can see that it proceeds uniformly along a wide range of cutting velocity (Fig. 5). The alteration of the segment shearing angle ϕ_{Seg} with different cutting velocities and cutting heights is negligible. An increasing cutting velocity and/or cutting depth h results in a higher chip segmentation. Chip segmentation means that, in contrast to continous chips, the chipping thickness is not constant and the chips have the form of a saw tooth (Fig. 5). The segmentation can be specified by the average distance of the peaks and the degree of segmentation, which is defined in Fig. 11. For high cutting velocities and large cutting depths the chips breaks into fragments. The parameter λ (compression of chip) characterizes the relation of the average chip thickness before and after the cutting process. If λ is larger than 1, the chips get compressed, otherwise they are extended.

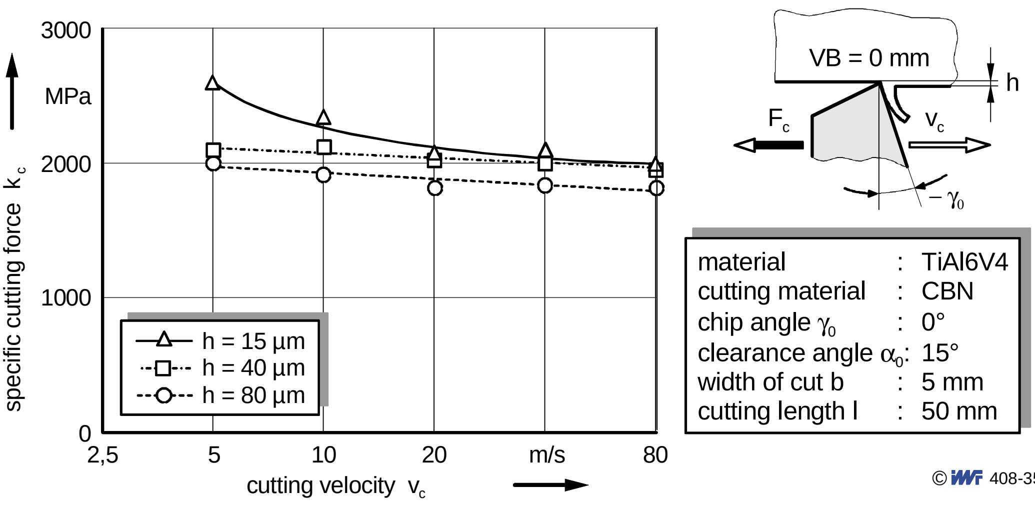


Fig. 4. Specific cutting force of TiAl6V4

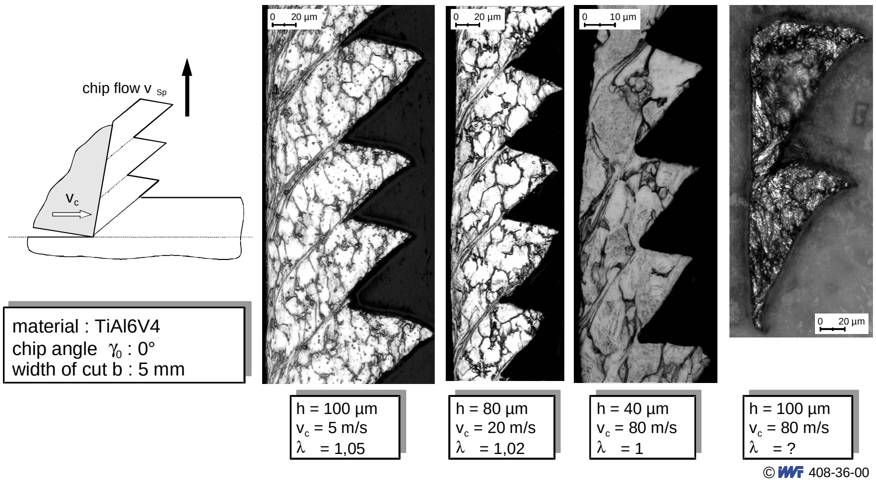


Fig. 5. Chip formation

Considering the specific cutting forces and therefore the stock removal energy for Inconel 718, one can see that they are about 50% higher than in machining TiAl6V4 (Fig. 6). The reason is the superior mechanical strength of Inconel 718. Compared to machining titanium alloys there is an explicit coherence between specific cutting force and cutting velocity. The reason for this differing behaviour is the different chip removal and

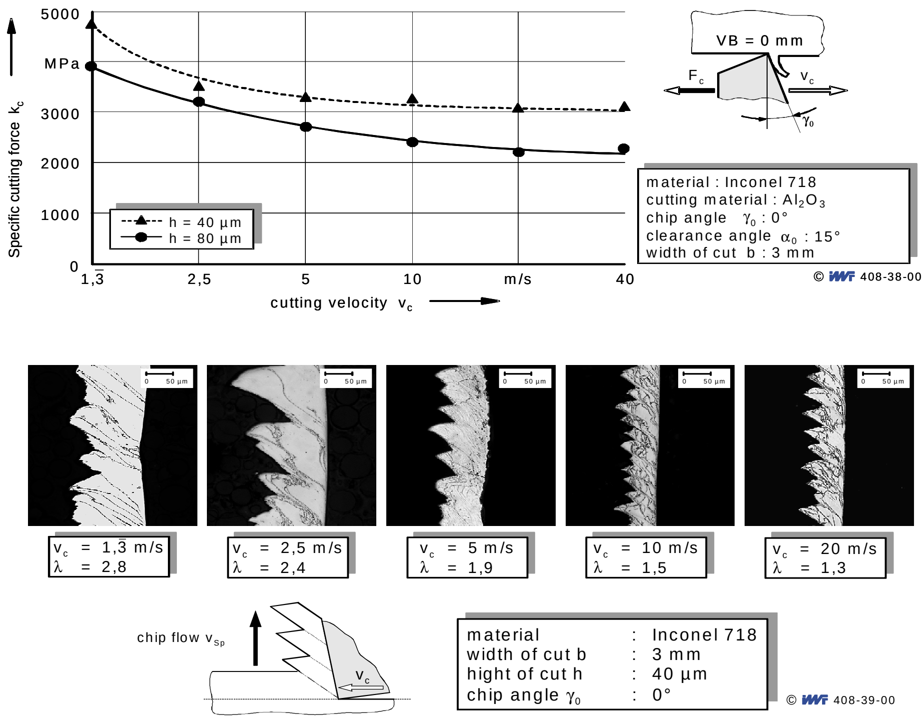


Fig. 6. Specific cutting force and chip formation of Inconel 718

formation process of these materials. In comparison to the machining of TiAl6V4 the chip formation of Inconel 718, especially at low cutting velocities, is very unbalanced. There is often a part with continuous chips. An increase of cutting depth or cutting velocity has the effect that the chip segmentation becomes more important. To sum up, a variation of cutting parameters of Inconel 718 affects the chip formation more when machining TiAl6V4.

The reduction of the specific cutting force with an increase of the cutting velocity results from the thermal softening of the basic material due to the rising cutting temperatures. The increasing temperature results in a decrease of strength of the grain boundary and an improved possibility for moving of the lattice dislocations. Both phenomena result in a decrease of resistance up to deformation and therefore to a reduction of the specific cutting forces.

3.2. INFLUENCE OF TOOL CHIP ANGLE

In order to examine the influence between the degree of deformation and the required specific stock removal energy two tools with a different chip angle (0 and -30°) were used for cutting TiAl6V4 and Inconel 718.

In Fig. 7 one can see, that the specific cutting force for a tool with a chip angle of -30° at a cutting velocity of 5 m/s is about 50% higher than for a tool with a chip angle of 0°. With increasing cutting velocity the specific cutting force nearly remains at this level whereas the specific cutting force for the tool with the negative chip angle decreases. At a cutting velocity of 80 m/s the specific cutting force is comparable (~2000 MPa). This indicates that, concerning the required stock removal energy, the chip angle and thus the degree of deformation during the cutting process becomes less important with increasing cutting velocity.

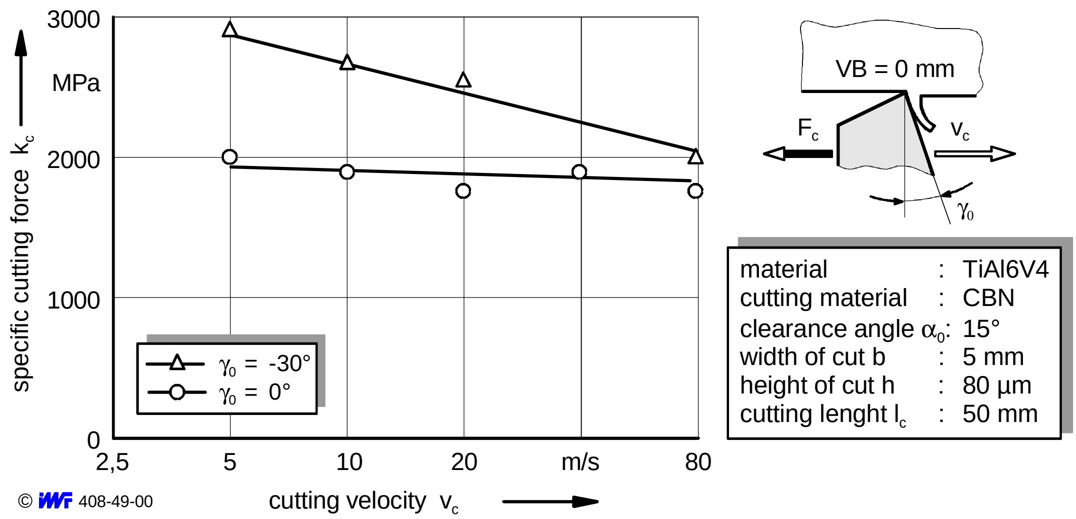


Fig. 7. Influence of a negative chip angle on the specific cutting force (TiAl6V4)

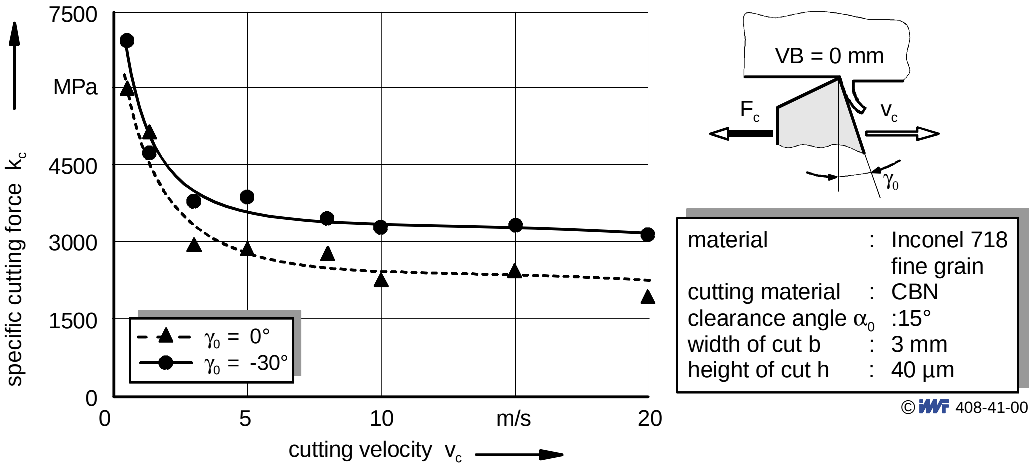


Fig. 8. Influence of a negative chip angle on the specific cutting force (Inconel 718)

Overall the specific cutting forces for Inconel 718 are higher than during the machining of TiAl6V4 due to the higher mechanical strength.

3.3. INFLUENCE OF STRUCTURE

Subsequently, the influence of two different structures of Inconel 718 on cutting behavior was examined.

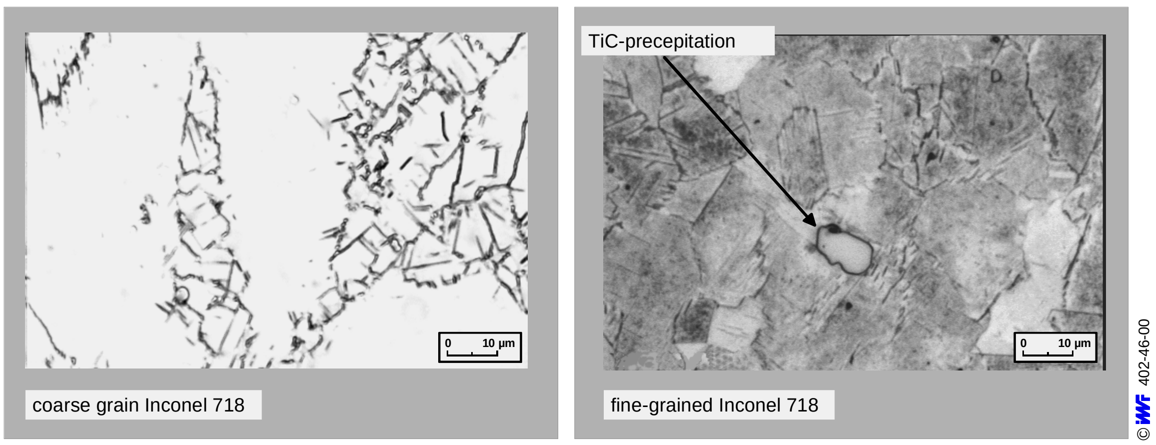


Fig. 9. Coarse (left) and fine grain (right) Inconel 718

The chemical composition of the material was identical, but the heat treatment was different. The coarse-grained structure shows a maximum grit size about 150 µm. The fine-grained structure is characterized by a considerably smaller grit size. The maximum grain-size of this structure amounts to a maximum of 40 µm and shows a more homogeneous distribution.

During the experimental examinations the influence of different structures on chip segmentation and specific cutting forces was observed and documented.

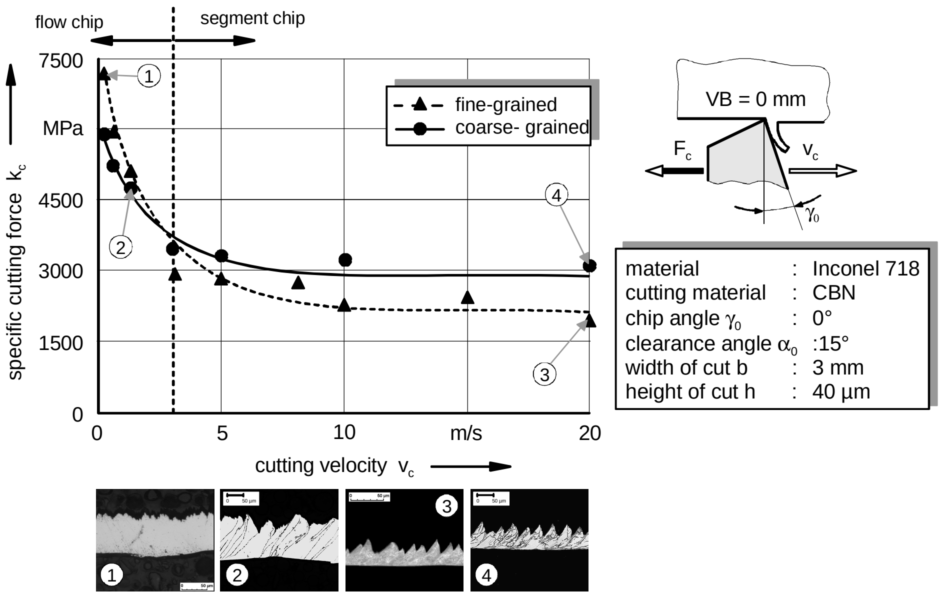
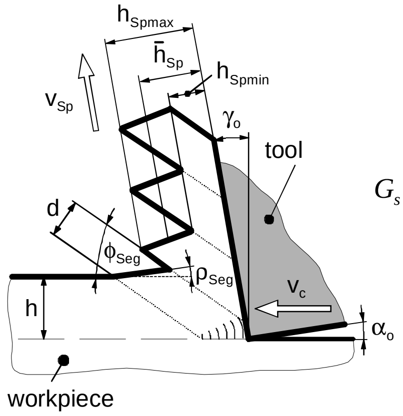


Fig. 10. Influence of structure on specific cutting force

Both structures show a decreasing specific cutting force with a rising cutting velocity. The reason is, as described before, the thermal softening of the material with rising temperatures. It is a fact that during machining the maximum temperature at the cutting edge can exceed 1000 °C [5], which results in a large increase of material temperature. With temperatures of more than 650 °C there is a strong decrease of material strength [6]. The decrease of the specific cutting force up to a cutting velocity of 3 m/s is caused by an increasing movement of lattice dislocations. Reaching a cutting velocity of 8 m/s the specific cutting force for both structures remains at a constant level. Overall, the specific cutting forces for the fine-grained structure at high cutting velocities are higher than for the coarse-grained structure. The reason is probably that there is a more pronounced sliding of grain boundaries.



$$G_s = \frac{h_{Sp\,\max} - h_{Sp\,\min}}{h_{Sp\,\max}}$$

Fig. 11. Definition of segmentation degree Gs

Regarding the chip formation in the range of low cutting velocities (< 3m/s), both structures show a relatively large amount of flow chip proportions. At a cutting velocity of 5 m/s, both structures show exclusively segmented chips, whereas the segmentation degree Gs, which is defined in Fig. 11, is higher for the fine-grained structure. So one can find a segmentation degree of 0.5 for the fine-grained and 0.37 for the coarse-grained structure at a cutting velocity of 20 m/s.

3.4. TEMPERATURE

In order to make a statement about the thermal load of the cutting tool by TiAl6V4 at very high cutting speeds, the temperature was measured by using an infrared camera. The experimental setup is shown in fig. 2. Due to the fact that the minimum measuring time of the camera mounts up to 40 ms and therefore exceed the maximum cutting time (10 ms at a cutting speed of 5 m/s), the only possibility to regard the conditions and temperatures at the cutting edge during cutting was to accomplish an additional FEM-simulation.

In Fig. 12 one can see the determined maximum temperatures at the cutting edge and the specific heat flow Q’. The heat flow volume decreased with a rising cutting velocity. The reason is, that the time for heat transfer decreases with a rising cutting velocity. Nevertheless, the maximum temperature increased continuously with the cutting velocity.

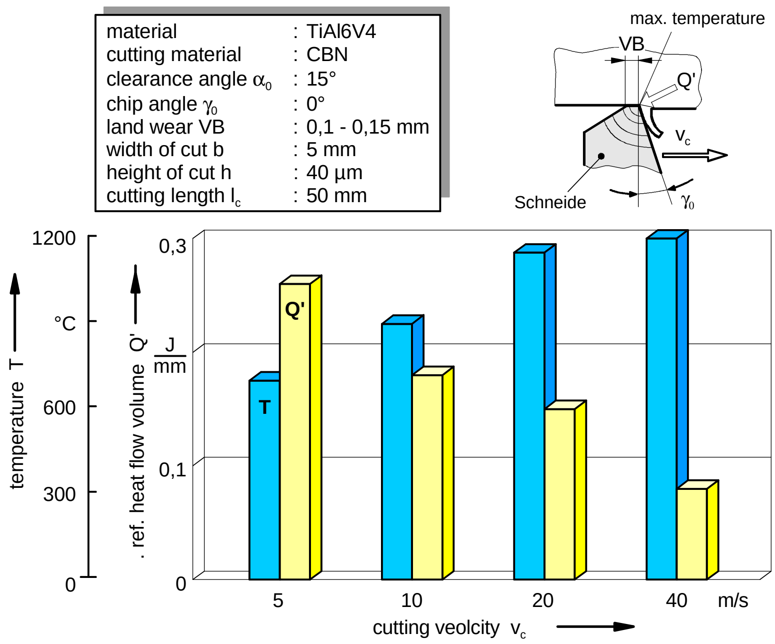


Fig. 12. TiAl6V4

This is caused by the fact that the heat disperses in a declining material volume and therefore local overheating occurs. Finally, the examinations show that during high speed cutting of AlTi6V4 maximum temperatures at cutting edge of up to 1200 °C are reached at the cutting edge. This means that the cutting material is not only loaded mechanically but also thermally. The combination of mechanical and thermal alternating loads is the reason for the short tool life, which is in a range of seconds and milliseconds for cutting speeds (up to 100 m/s) during the experiments on the high speed experimental rig [8].

4. CONCLUSIONS

It was possible to show that there are essential differences between Inconel 718 and TiAl6V4 concerning their machinability. It became evident that cutting TiAl6V4 with large cutting depths (> 40 µm) compared to the cutting edge radius shows a behaviour which is not dependent on cutting velocity and chip thickness concerning the specific cutting force. Whereas cutting with chip thickness in the range of the cutting edge radius or using a negative chip angle (-30°) shows a dependency on specific cutting forces and cutting velocities, which converges at high cutting velocities (80 m/s), large values of chip thickness and a chip angle of 0°. This means that the degree of deformation by cutting TiAl6V4 with an increase of cutting velocity becomes less important concerning the required stock removal energy. High speed machining of Inconel 718 clearly shows that the specific cutting force depends on cutting velocity and chip thickness. The decrease of the specific cutting force with rising cutting velocity is caused by thermal softening of the material by increased sliding of grain boundaries and a decline of grain boundary strength.

Concerning the chip formation the TiAl6V4 chips show distinctive chip segmentation for the whole cutting parameter range. By increasing cutting velocity or the chip thickness, the tendency to chip segmentation was increased. The chip formation of Inconel 718 alters with variation of the cutting velocity, chip thickness and structure. An increase of the cutting velocity and/or chip thickness or a decrease of structure grain size enforces the tendency to chip segmentation. For low cutting velocities there is often a part with continuous chips.. Solely segmented chips were documented for high cutting velocities, but even for very high cutting velocities the chip segmentation does not reach the same level as when cutting TiAl6V4.

By accomplishing a temperature measurement with an additional FEM-simulation it was possible to demonstrate that the temperature at the cutting edge during cutting superalloys for high speed machining can reach more than 1000°C. This means that during high speed cutting the cutting edge is heavily loaded by mechanical and thermal influences. Therefore, the demand on cutting materials for high speed cutting is exceptionally high.

The experiences gained can be used for specifying high performance cutting processes. The knowledge that the specific cutting force decreases up to 30% with increased cutting velocity helps to define the machine requirements or to choose the specific tool material. The increase of cutting velocity up to the point where the chips are segmented helps to improve chip removal.

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