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A FEM and Experiment Study on High Speed Machining of Nickel-Based Superalloy GH4169

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Abstract. As a typical difficult-to-cut material, the nickel-based superalloy *GH4169* has been used in many kinds of aeronautical key structures and turbine components because of its high yield stress and anti-fatigue performance even in high temperature. In this paper, finite element method (*FEM*) is introduced to study the saw-tooth chip formation in detail. By the way of Lagrange approach, adiabatic shear band (*ASB*) is simulated and the chip forming mechanism is interpreted by adiabatic shearing theory via the comparison of two models, one of which has a failure criterion and another not. The comprehensive comparison and analysis of chip morphology between simulation and experiment are also presented in this paper.

Introduction

GH4169 is manufactured under the *Microcast-x* technique. By this technique, the ASTM 3~4 grade (0.07~0.11mm) crystalline grain can be got. Special forming process makes *GH4169* a kind of extremely difficult-to-cut material. Some characteristics which are responsible for its poor machinability have been summarized by researchers [1~3].

Research on the saw-tooth chip formation is helpful to study the machining mechanism of superalloy. This kind of chip was firstly found in the forefront of ballistic studies of projectile penetration (Zener, 1948). Then the same phenomenon was found in machining titanium alloy and adiabatic shearing was firstly used to explain the saw-tooth chip formation mechanism by Shaw et al. (1954). Subsequently, Nakayama suggested a new brittle fracture theory of saw-tooth chip formation based on many experiments (1974). It suggests that original cause of saw-tooth chip formation is periodic fracture which initiates at the free surface and proceeds downward to the tool tip. In recent 20 years, most of the researchers suggest adiabatic shear as the origin of saw-tooth chip formation [4~6]. Only few studies could be found that explained the relationship of adiabatic shearing and brittle crack in detail. In this work, the commercial finite element software *ABAQUS/Explicit* will be used to study the saw-tooth chip formation of *GH4169* under a wide range of cutting speed. Finite element model with a material failure criterion will be introduced to simulate brittle crack at free surface and *ASB* in primary shear zone in order to find the original cause of saw-tooth chip. Simulation results about chip morphology indexes will be compared with the experiment work.

Experimental Procedure

Superalloy *GH4169* turning experiments are all carried out on INDEX G200 turning center. The uncoated commercial carbide insert is used, which has a tool cutting edge angle 95°, clearance angle -5°, and rake angle 0°. Cutting depth is 1mm and the feed rate is 0.15mm/rev. Cutting speed is distributed from 15m/min to 250m/min. The chip morphology is analyzed by Philips XL30–FEG scanning electronic microscope (*SEM*).

Finite Element Model

Initial Configuration. A 2D fully thermo-mechanically coupled orthogonal cutting model was developed with a pre-defined cutting routine (Fig.1). Uncut chip layer is designed to a parallelogram because oblique mesh is easier to form a chip along the tool face and prevent the occurring of mesh distortion under the condition of negative rake angel. Fine mesh density is required to represent the severe deformation in *ASB*. Generally speaking, length and width of parallelogram mesh should be set below 10μm if an adiabatic shear band would perhaps appear. Here these two values are all 8μm.

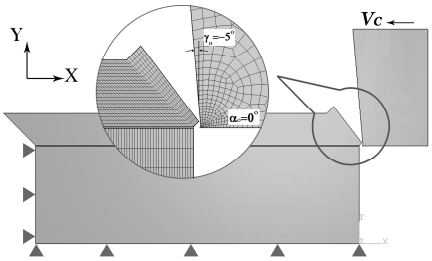


Fig.1 Finite element model with pre-defined uncut chip layer

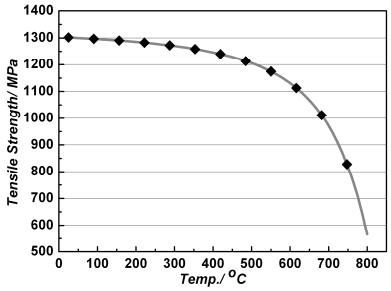


Fig.2 Tensile strength under different temperature

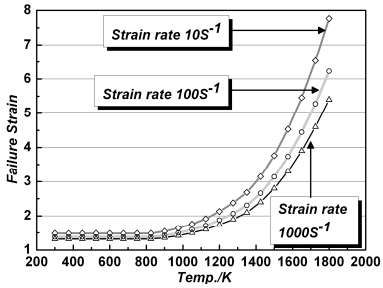


Fig.3 Failure strain under different strain rate

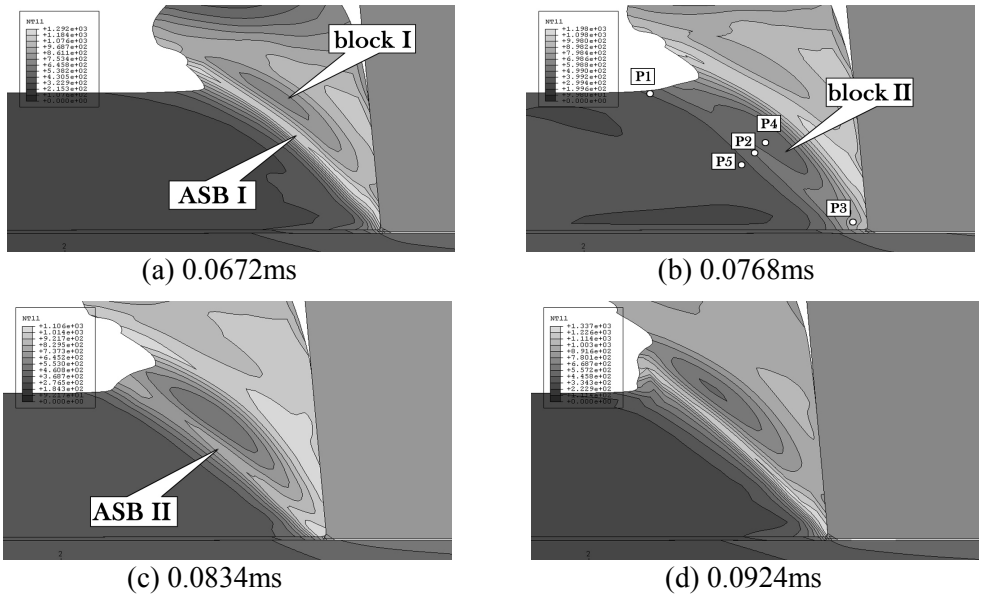
Element Failure Model. Here a Lagrange formulation is used and this formulation can simulate steady and unsteady chip forming process. The stress-strain curves [7] of Inconel718 (*GH4169*) when compressed at a strain rate of $100s^{-1}$ over the range of temperatures were used. Exact stress values were induced by the yield strength from handbooks. Elements have a material failure criteria based on equivalent plastic strain. A damaging parameter *w* defined as followed equation [8]:

$$w = (\bar{\varepsilon}_0^{\,pl} + \sum \Delta\bar{\varepsilon}^{pl}) / \bar{\varepsilon}_f^{\,pl} \tag{1}$$

Where $\bar{\varepsilon}_0^{\,pl}$ is the initial equivalent plastic strain value, $\Delta\bar{\varepsilon}^{pl}$ is the equivalent plastic strain increment of every increment step, $\bar{\varepsilon}_f^{\,pl}$ is the failure strain. Elements fail when the damage parameter *w* exceeds 1. Considering the influence of strain rate on material brittleness in material failure simulation, tensile strength of *GH4169* under different temperature is adopted from handbook and regarded as the same under different strain rate (Fig.2). Then with the help of this tensile strength chart and the constitutive relationship established on micro-structural evolution [9], equivalent plastic strain (*PEEQ*) at failure under different strain rate can be got in Fig.3 and failure strain under higher strain rate can be fitted by software easily.

Results and Discussions

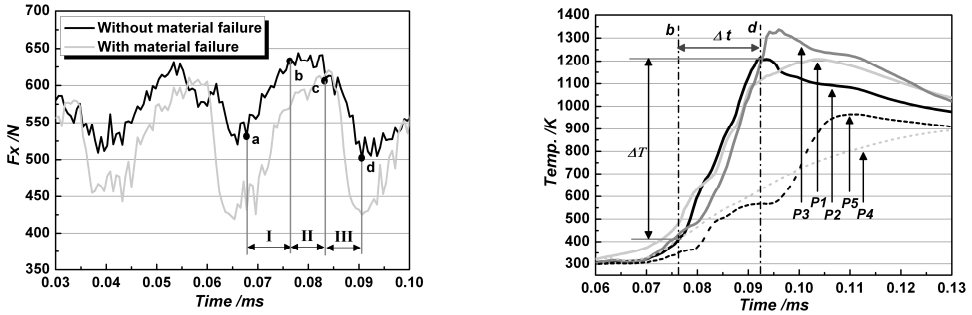
Chip Formation Mechanism. Early adiabatic shear theory suggests the cause of saw-tooth chip formation is a catastrophic thermoplastic instability where the decrease in flow stress due to thermal softening associated with an increase in strain more than offsets the associated strain hardening (Shaw et al., 1954). Subsequent researches prove that the original cause of saw-tooth is periodic fracture at free surface of the workpiece (Nakayama, 1974). According to this theory, the onset of saw-tooth chip can be predicted by fracture mechanics instead of thermal analysis. Under the cutting speed 250m/min and other parameters mentioned before, the stage of a segment developing without material failure was simulated in detail as the followed Fig.4 in order to observe the thermal softening under the condition where there is no brittle crack. At the predicted shear zone, temperature changing of 5 points P1~P5 are concerned. P1, P2, P3 lies near the free surface, in predict shear zone and near the tool tip respectively, while the other two points are very close to the predicted shear zone. Perturbation of the cutting force in x direction is also recorded.



(a) 0.0672ms (b) 0.0768ms

(c) 0.0834ms (d) 0.0924ms

Fig.4 The stage of a segment developing & distribution of node temperature without failure (a_p=1.0mm, f_z=0.15mm/rev, v_c=250m/min, γ_o=-5°,α_o=5°)



(a) Cutting force simulation in x direction (b) Node temperature of the 5 points

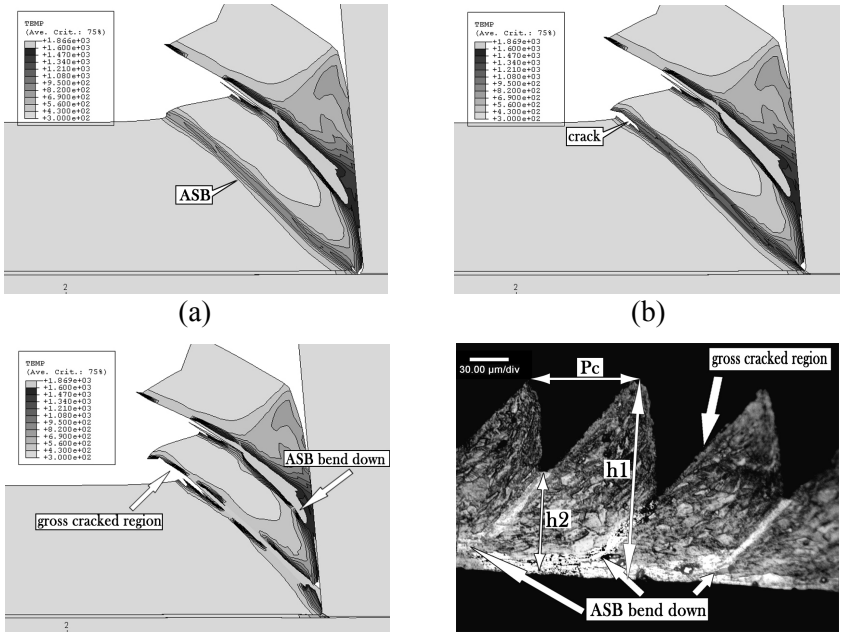
Fig.5 Force and temperature results by finite element analysis (FEA)

At 0.0672ms (Fig.4-a), *block I* and *ASB I* have formed and the lowest shear stress in *ASB* let the cutting force locate in valley of the curve (Fig.5-a). The moment from 0.0672ms to 0.0768ms is the main phase (*phase I* in Fig.5-a) for *block II* to shaping. Enough shear stress must be supplied to build up the *block II* and make it climb up the tool rake face because high temperature in *ASB I* is too late to influence *block II*, so cutting force goes up all through the *phase I*. The moment from 0.0768ms to 0.0834ms is the main phase (*phase II* in Fig.5-a) for *ASB II* to shape. On one hand, shear stress in relatively cool *block I* must be supplied continually for it to distort and climb up, on the other hand rapidly rising temperature in *ASB II* makes the stress go down beside it. Comprehensive influence of both keeps the cutting force well balanced about 625N. In *phase III* adiabatic shearing continues to go in *ASB II*, but the *block II* would not distort any more. So the force goes down to a valley once more at 0.0924ms (Fig.4-d).

From above analysis we can know that *phase II* and *phase III* are the main phases the adiabatic shearing occurs. Fig.5-b records the temperature changing of the 5 points in Fig.4-b. In this period, temperature at P1, P2 and P3 rise beyond 700K, while the other two, below 250K. Comparison suggests that temperature rising occurs in a narrow band which connects by P1, P2 and P3 during a very short time of 0.0156ms. This periodic thermoplastic instability let saw-tooth chip come into being. This principle is also the main character of the adiabatic shear theory.

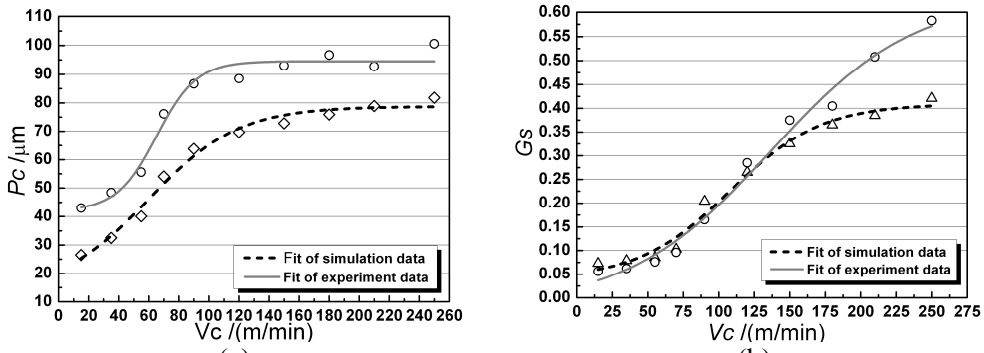
Here a shear failure criterion with a changeable failure strain (Fig.3) is hired in *FEM* to simulate the crack phenomenon in order to interpret the relation between brittle crack and adiabatic shearing. In Fig.6-a, concentrated temperature distribution obviously shows the appearance of *ASB*. Relatively low temperature which can be shown in Fig.5-b and high strain rate at free surface makes the failure

strain lower than other place, so the crack comes forth near the free surface (Fig.6-b). As cutting goes forward, this crack increases its dimension and become a gross cracked region which is firstly suggested in Nakayama's theory. This result has some differences with former research because a more authentic shear failure criterion is used here. At the same time, adhesion effect between workpiece and tool rake face in high temperature makes the first *ASB* bend down (Fig.6-c). Comparison of Fig.6-c and Fig.6-d accord with each other in shapes of gross cracked region and the *ASB* bend.



(a) (b) (c) (d)

Fig.6 Temperature distribution in *FEM* with material failure and saw-tooth *SEM* (a_p=1.0mm, f_z=0.15mm/rev, v_c=250m/min, γ_o=-5°,α_o=5°)



(a) (b)

Fig.7 Relations between saw-tooth indexes and the cutting speed from simulation & experiment

Chip Morphology. Different chip morphology was observed from low speed to high speed under metallurgical phase microscope. The saw-tooth seems to be short and shallow when in low speed cutting, while in high speed cutting, relatively long and deep. Here two parameters *Gs* (degree of segmentation) and *Pc* (pace of tooth) are used to depict the severity degree of saw-tooth chip formation. Index *Gs* is defined as followed [10], where h_1 is height measured from chip bottom to tooth tip, h_2 is height measured from chip bottom to tooth bottom (Fig.6-d):

$$G_S = (h_1 - h_2)/h_1 \tag{2}$$

Changing trend of the two indexes *Pc* & *Gs* with the rise of cutting speed is summarized in the following Fig.7. As the using of equal friction coefficient on the rake face and assumption of the

absolute sharp cutting edge, there is deviation on the absolute values between the two results. An increase in speed gives rise to an increase in strain rate which increases brittleness. On the other hand, an increase in cutting speed increases the temperature of the chip which decreases brittleness [11]. From results, *Gs* and *Pc* all go up with the speed. Degree of segmentation is not so apparent when the cutting speed is below 55m/min. Influence of the two factors reaches a balance in this speed range. When speed exceeds 70m/min, the two indexes rise faster because the influence of the thermal softening action dominates.

Conclusions

With the help of Lagrange approach and some other *FEM* technology, saw-tooth chip morphology when machining *GH4169* was simulated. Saw-tooth formation was interpreted with adiabatic shear theory by analyzing the change of cutting force and node temperature around *ASB*.

By using of material failure model the brittle crack can be seen at the free surface after the appearance of *ASB*. Finite element model without a failure criterion can also develop a saw-tooth chip in spit of the lack of brittle fracture character. This phenomenon discovers the adiabatic shearing to be original cause of saw-tooth chip formation instead of brittle crack.

Typical saw-tooth indexes *Pc* & *Gs* were observed to change with the cutting speed apparently. At 15~55m/min, brittleness improvement can be accessible near to the thermal softening. So they all increase gently. At 70~250m/min, thermal softening enhances and hence the two indexes increase faster.

Acknowledgements

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