Materials Research Proceedings 44 (2024) 233-240 https://doi.org/10.21741/9781644903254-26

Effect of grain size on blank holder force of fine micro-blanking for Inconel 718 superalloy foils

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Keywords: Fine Micro-Blanking, Grain Size, Blank Holder Force, Revised Empirical Formula

Abstract. Regarding product miniaturization, there is a noticeable difference between micro-blanking and macro-blanking in terms of the quality of the parts and the metal deformation behavior. In this paper, fine micro-blanking simulations were conducted on Inconel 718 foils with a thickness of 100 μm and different grain size to investigate the effects of different blank holder force on the fracture length of blanking surface. The results showed that the empirical (macro) formula of blank holder cannot apply to fine micro-blanking. The fracture length gradually decreases with the increase of blank holder force. And as the grain growth, the blank holder force to obtain a micro-blanking surface with full burnish length and no fracture zone was smaller. Based on the effect of grain size and blank holder force, a revised empirical formula of blank holder force was established for fine micro-blanking. Then, the fine micro-blanking experiments of Inconel 718 superalloy foils were conducted to evaluate the feasibility for the revised empirical formula of blank holder force. This work may contribute to the selection of forming force for fine micro-blanking applications.

Introduction

There are strict requirements for micro-hole components in many industrial domains, such as micro-electromechanical systems (MEMS), electrical/electronic devices, and medical systems [1, 2]. Various manufacturing technologies have emerged to satisfy these requirements. There are innovative techniques for manufacturing micro components including micro-hole like electrical discharge machining (EDM), exciter laser cutting, continuous force drilling, electromechanical drilling, and micro-blanking [3-7]. Micro-blanking is a straightforward, low-cost, highly productive approach that remits excellent mechanical properties and good surface quality [8, 9].

Micro-blanking is a plastic deformation technology that has been extensively researched for several decades [10-13]. Regarding product miniaturization, there is a noticeable difference between micro-blanking and macro-blanking in terms of the quality of the parts and the metal deformation behavior. Xu [14] et al. conducted forming limit experiments of metal sheets under different conditions based on miniaturized Holmberg and Marciniak tests. They found that the forming limit curve shifted downward with the decrease of the thickness-to-grain-size ratio. Geiger [15] et al. carried out theoretical analysis, numerical simulation, and experiments to find that the miniaturization of the workpiece dimensions can lead to a change in the boundary conditions in metal forming. Wang [16] et al. conducted micro bulk forming, and found that the billet size has a direct influence on the deformation behavior. This phenomenon is known as the “size effect”. The micro-forming process is accompanied by significant size effects, which reduce the formability of materials and the accuracy of parts [17]. Xu et al. [18]used brass foils with different grain size to conduct a serious of micro-blanking experiment and found the blanking force curves

Materials Research Proceedings 44 (2024) 233-240 https://doi.org/10.21741/9781644903254-26

are repeatable for fine-grained specimens, but the curves of coarse-grained specimens has a tremendous difference for maximum blanking force and curve profile.

The fracture zone on the blanking surface will impact the service behavior and useful life of micro components and industrial equipment [19-21]. But the study results indicted many micro-blanking method can not to obtain the micro-blanking surface without the fractue zone, such as the rigid micro-blanking, laser dynamic micro-blanking, electromagnetism-assisted flexible micro-blanking, underwater shock wave-assisted flexible micro-blanking and ultrasound-assisted flexible micro-blanking [22-27]. In order to reduce the affect of fracture zone for service behavior and useful life, we proposed the fine micro-blanking method to fracture the micro components based on the fine blanking process and conducted micro-blanking experiments for Inconel 718 foils with different grain size [28, 29]. The results indicted the size effect during plastic deformation for submillimeter metal plates renders the empirical formula for (macro) blanking force inapplicable to fine micro-blanking. However, it is not possible to determine the exact blank holder force and counter force for fine micro-blanking.

Therefore, considering the problems existing in current fine micro-blanking research, this study conducted the finite element simulation to determine the exact process force. Through theoretical analysis, it is proved that increasing the blanking holder force is an effective method to improve the fine micro-blanking quality. The fine micro-blanking simulations were conducted on Inconel 718 foils with a thickness of 100 μm and different grain size to investigate the effects of different blank holder force on the fracture length of blanking surface. This study is helpful for further understanding the grain size effect, and provides technical guidance for the plastic forming of miniaturized key components.

Experimental materials and method

Inconel 718 sheets with thickness of 0.1 mm and were selected as experimental materials. Their chemical composition is shown in Table 1. Fig. 1 presents the original microstructure of the Inconel 718 foils. As shown in Fig. 1(a), the original grains were fine equiaxed crystals. The XRD pattern demonstrates that the matrix γ phase was dominant in the alloy, and there were no obvious γ', γ'', or δ phases. Therefore, it was assumed that there were no precipitated particles in the original foils.

Table 1. Chemical composition of Inconel 718 (wt. /%).

C	Cr	Ni	Co	Mo	Al	Ti	Fe	Nb	B	Mn
0.008	18.5	51.6	1.0	3.3	0.8	1.15	Bal.	5.5	0.006	0.35

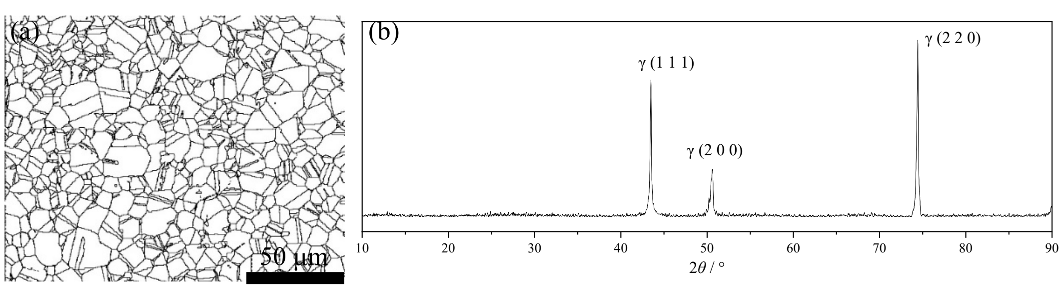

Fig. 1. Original microstructure of Inconel 718 foils: (a) microstructure; (b) XRD diffraction pattern.

The material is in the solid solution state as-received. To avoid the influence of the second phase and change the grain size on the on the mechanical properties of Inconel 718 foil, the time was 1h and temperatures of solid solutions were respectively 1050℃, 1100℃, and 1150℃, as all second phases dissolved by 1037℃. The grain size of Inconel 718 foils was dispalyed in Table 2.

Materials Research Proceedings 44 (2024) 233-240 https://doi.org/10.21741/9781644903254-26

Table 2. The average grain size after solid solution treatment for the Inconel 718 alloy.

Number	Average grain size / μm
O	9.3
A1	12.69
A2	52.04
A3	93.45

With the die structure and Deform-3D software, we applied FE simulation to analyze the deformation behavior of four different states of foils during Inconel 718 fine micro-blanking. The fine micro-blanking part is a round hole with thickness of 0.1 mm and radius of 0.25 mm. The FE model of the fine micro-blanking process including a punch, holder blank, metal foil, female die, and counter punch was established as shown in Fig. 2(a). We also built a quarter-size FE model based on the axisymmetry of the target part for further analysis at a reduced calculation burden and enhanced computation speed. The mesh type of the metal sheet in the FE model was a tetrahedral mesh, and the mesh was finely divided around the shear band to improve the accuracy of FE simulation. In Fig. 2(b), A and B indicate the symmetry surface of the FE model, and C is the finely divided mesh. The friction condition was the cold forming of steel dies, and its coulomb friction coefficient was 0.12. The speed of the punch movement was 0.2 mm/s, and the stroke of the punch was 0.12 mm. The Modified-Voce model and normalized Freudenthal fracture criteria were used as material models in the simulation.

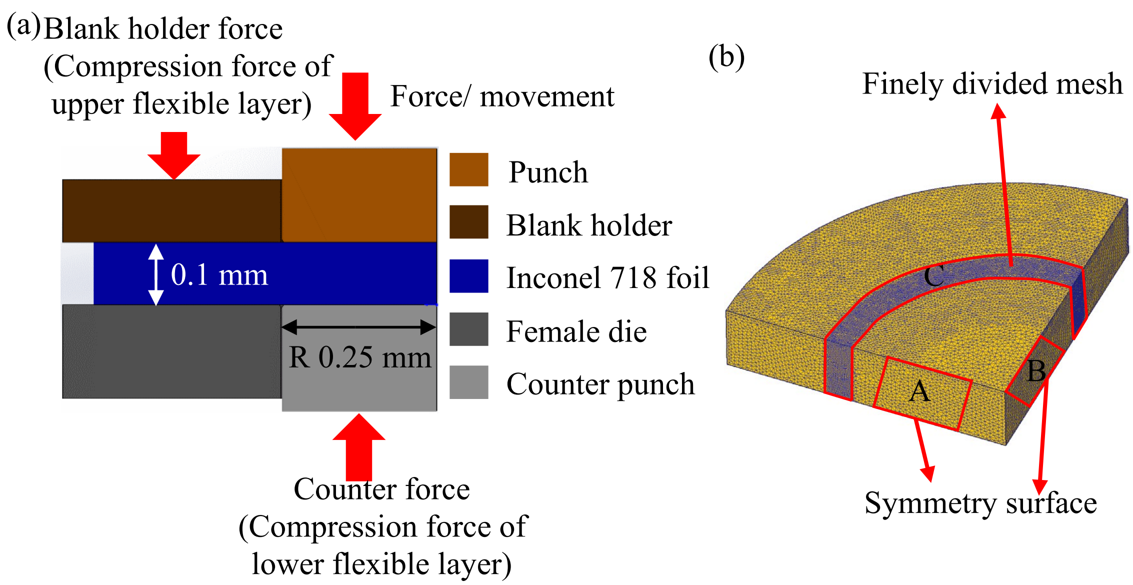

Fig. 2. Finite element model of fine micro-blanking Inconel 718 foil: (a) fine micro-blanking model, (b) workpiece mesh.

The materials constitutive model was applied to conducted the finite element simulation of fine micro-blanking, as shown in Eq. 1. The model includes the surface flow and internal flow of the material and considers the dependent variables and grain size.

$$\sigma=\eta m_1 a_1 \varepsilon^{n_1}+(1-\eta)\left(m_2 a_1 \varepsilon^{n_1}+\frac{a_2 \varepsilon^{n_2}}{\sqrt{d}}\right) \quad (1)$$

where η is the grain size factor, representing the ratio of the number of surface grains to the total number of grains in the sample. m_1 is the orientation factor of the grain on the surface, and m_2 is the orientation factor of the internal grain, a_1, a_2, q_1, q_2, n_1, and n_2 are material constants. These parameters are shown in Table 3 and the critical damage values of Inconel 718 foils with different grain sizes was displayed in Table 4.

Table 3. The parameters of material constitutive model.

Parameters	m_1	m_2	a_1/MPa	a_2/MPa	n_1	n_2
Value	2	3.06	263.78	8872.61	0.12	2.02

Table 4. The critical damage values of metal foils with the different grain size.

Number	Critical damage values
O	5.13
A1	3.48
A2	2.68
A3	2.22

Results and discussion

When the blank holder force is within a reasonable range, the blanking quality of micro-blanking pieces will be improved by the increase of blank holder force. Fine macro-blanking uses Eq. 2 to calculate the blank holder force.

$$F_{hb} = k_{bh} F_{max} \tag{2}$$

where F_{bh} is the blank holder force, F_{max} is the maximum blanking force and k_{bh} is the process coefficient of blank holder force. When k_{bh} is 0.5, the blanking quality of fine macro-blanking is good. Therefore, this study slected 0.5 as the k_{bh} to donducted the fintie element simulation for fine micro-blanking of Inconel 718. However, there are the fracture zone on the blanking surface, as shown in Fig. 3. And the fracture length is increase with grain size increase. It indicates the stress state in the shear deformation zone is changed from mean compressive stress to tensile stress, and cannot restrains the ductile fracture. In the other words, the empirical (macro) formula does not exactly to describe the fine micro-blanking when k_{bh} is 0.5. The small blank holder force caused the facture zone on the blanking surface. Therefore, the k_{bh} need to be improved.

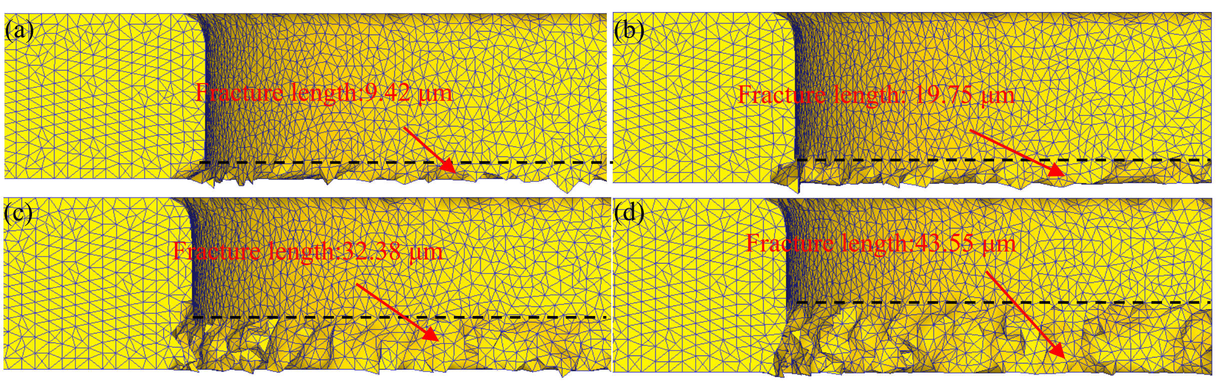

Fig. 3. Finite element simulation results: (a) d=9.3 μm, (b) d=12.69 μm, (c) d=52.04 μm, (d) d=93.45 μm.

The simulation results which using the different k_{bh} were dispalyed in Fig. 4. With the increase of process coefficient for blanking force, the fracture length of Inconel 718 foils with different grain sizes decreases gradually, until there is nofracture zone. It means that the process coefficient of blanking force no longer affect the quality of blanking surface when the blanking surface is fully brunish.

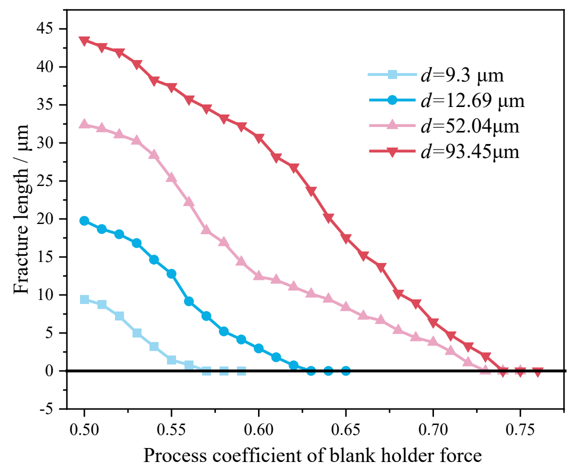

Fig. 4. The relationship between k_{bh} and fracture length.

The correlation analysis was conducted to explore the relationship between the k_{bh} and its influencing factors during fine micro-blanking for Inconel 718 foil, and the results are shown in Fig. 5. The results indicated the applicable k_{bh} increase with the grain size and yield-tensile strength ratio, decrease with the maximum tensile strength. Compared with the absolute value of correlation coefficient, it is more closely related to grain size and maximum tensile strength. And the maximum tensile strength is impacted by grain size.

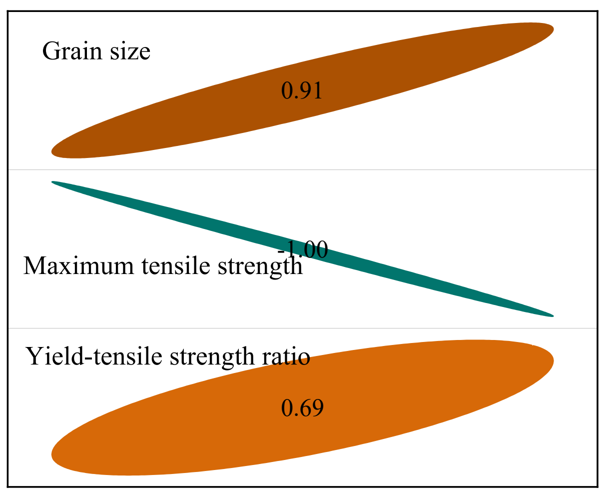

Fig. 5. The result of correlation analysis.

Therefore, we proposed that using the relationship between grain size and k_{bh} to modify empirical formula of blank holder force for fine micro-blanking, as shown in Fig. 6. To quantitatively evaluate the modified result, the relative error is introduced to assess the fitting accuracy. Through comparison and observation, it was found that the absolute relative errors of Inconel 718 thin plates with different grain sizes were all less than 2%. The modify empirical formula of blank holder force for fine micro-blanking can be described as follows:

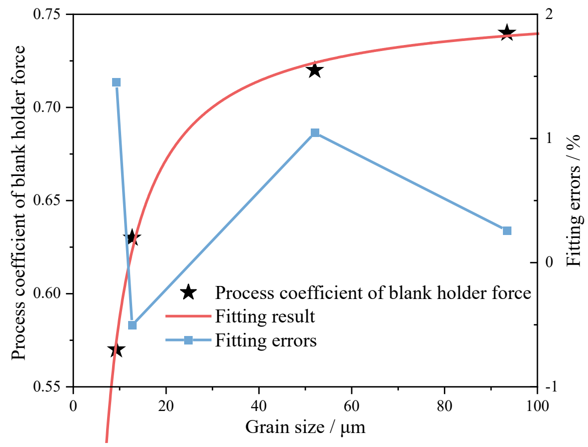

Fig. 6. The relationship between k_{bh} and grain size.

$$k_{bh-g} = 0.76 + \frac{1.69}{d} \tag{3}$$

The fine micro-blanking and modified empirical formula of blank holder force were used to fabricate the components of Inconel 718 foils with different grain size, as shown in Fig. 7. These size of components is similar to component model. And it is found that the fully burnish zone without fracture were obtained on by observing the blanking surfaces in the black frame.These results indicate that the modified empirical formula of blank holder force can be applied to manufacture micro components for fine micro-blanking.

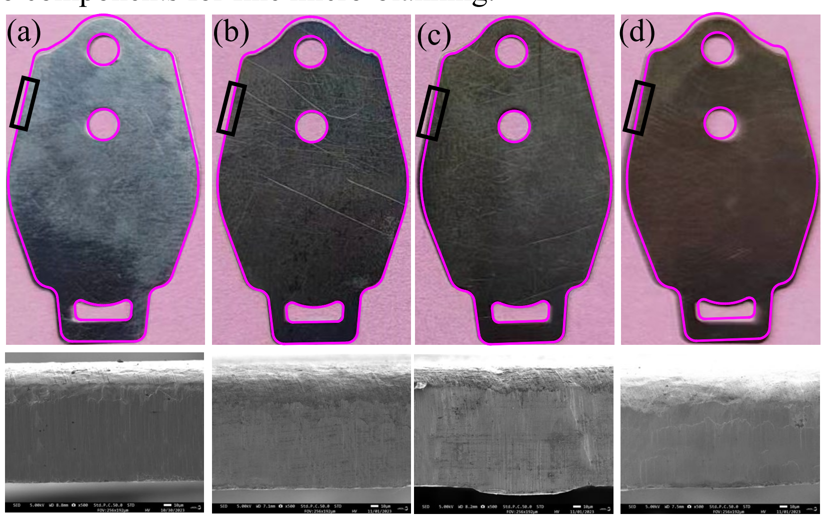

Fig. 7. Fine micro-blanking results: (a) d=9.3 μm, (b) d=12.69 μm, (c) d=52.04 μm, (d) d=93.45 μm.

Conclusion

In this study, we used fine micro-blanking technology and finite element simulation to determine the exact blank holder force and counter force for fine micro-blanking. When k_{bh} is 0.5, the empirical (macro) formula does not exactly to describe the fine micro-blanking and the fracture length is increase with grain size increase. With the increase of k_{bh}, the fracture length of Inconel 718 foils with different grain sizes decreases gradually, until there is nofracture zone. Due to k_{bh} is impacted by grain size, we established a modified empirical formula of blank holder force that is suitable for the fine micro-blanking based on the relationship between grain size and k_{bh}. This study lays a theoretical foundation for the miniaturized plastic forming of key components, and meets the needs of current development.

Acknowledgments
This work is grateful for the financial supports from the National Natural Science Foundation of China (52275371) and the National Key R&D Program of China (No. 2020YFA0714900).

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