A Novel Force Variation Fine Blanking Process for the High-strength and Low-plasticity Material

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Research Article

Keywords: Fine-blanking, Force variation, Neural network, Genetic algorithm

Posted Date: November 29th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-1094395/v1>

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Version of Record: A version of this preprint was published at Metals on March 8th, 2022. See the published version at <https://doi.org/10.3390/met12030458>.

Abstract

Fine blanking is a kind of metal forming process with the advantages of high precision, good surface quality and low cost. Influenced by the concept of lightweight, a large number of metal materials with high strength are widely used in various fields. High strength materials are prone to be cracked during plastic deformation due to their poor plasticity, which limits the application range of them. This paper proposed a force variation fine blanking process for high-strength and low-plasticity materials. At the same time, a method to find the curve of forming force for this novel process was presented. A 2D finite element fine blanking model was established for the TC4 material. Combining genetic algorithm and neural network methods, a model was built up to find the optimal forming force loading curve. The parts fabricated by force variation loading and constant loading fine blanking process were compared through experiments. The mechanism of force variation fine blanking is also revealed. The forming force mainly affects the length of clean cutting surface by affecting hydrostatic stress. According to the ultimate optimal loading curve, the forming force should be kept at a low level in the early stage of blanking stroke, and increased gradually in the ending stage. In the application of force variation fine blanking, the part with long length of clean cutting surface can be obtained with lower die load.

1 Introduction

Fine blanking is an advanced sheet metal plastic forming process which derived from the conventional blanking process. In the fine blanking process, only one punching stroke is required to obtain parts with high surface quality and dimensional accuracy. Compared with conventional blanking, the efficiency is greatly improved and the manufacture cost in the production process is reduced. Currently, it is widely used in aerospace, automobile, shipbuilding and other manufacturing fields ^[1].

To gain high quality cutting surface of fine blanking parts, the key is that the material in the shear deformation zone undergoes plastic deformation as much as possible and delays the occurrence of fracture behavior ^[2]. For this reason, it is necessary to ensure high hydrostatic stress state inside the material. It depends on the blank holder and the counter punch in the fine blanking die structure. The V-ring can largely limit the outward flow of internal materials. It cooperates with the counter punch to improve the hydrostatic stress and plastic forming ability of the material in the shear deformation zone ^[3], and finally obtain high-quality parts ^[4].

Based on the above basic principles, due to severe plastic deformation of the material during the processing, the material is required to possess good plasticity. Therefore, some materials need to be spheroidized annealed before fine blanking to improve their plasticity ^[5]. The materials of parts often pursue higher specific strength during selection, when lightweight is becoming a hot topic nowadays ^[6]. As a representative of these material, titanium alloys have excellent mechanical properties and are extensively used. Applying fine blanking can improve the overall performance of titanium parts, reduce the load of the die, and expand the application range of titanium alloys. But their plasticity is poor, which makes them prone to fracture during the plastic process ^[7].

At present, there are some studies on fine blanking of high strength materials. Gram et al. ^[8] verified the possibility of fine blanking of high strength materials through the experimental study of various strength materials. Zhao et al. ^[9] studied the behavior of DP600 high-strength steel during fine blanking, and discussed the role of shear damage in induced tearing. Although the above research content involves the fine blanking of high strength materials, it does not provide a solution to the problem of crack during the forming process. If the process force of high strength material is calculated according to the empirical formula ^[10], the forming force value will be very large. According to the theoretical model proposed by Yin et al. ^[11], die wear is positively correlated with blank holder force and counter punch force. Moreover, high forming force also brings a huge load to the mold, which greatly causes the punch to break and reduces the tool life.

When encountering this problem, most researchers focus on the life of the die ^[12]. Fine blanking of high-strength steels leads to an increase of the wear of fine blanking punches. Klocke et al. ^[13] found that deep rolling has a potential to improve the wear resistance of fine blanking punches when processing high-strength material and a novel profiled deep rolling tool is developed in this work. Bear et al. ^[14] performed a comprehensive numerical study on the influence of process parameter. It allows for prediction of the punch load during fine blanking of high-strength steels. However, they only explored from the aspect of the die load, not from the forming parameters.

Based on the above problem, this paper proposed a new force variation fine blanking process to form high-strength materials. It means that the value of the forming force is not constant during the blanking process. Forming force generally includes three parts, namely, the main blanking force, blank holder force and counter punch force. But in fine blanking process the main blanking force is imposed by the press to make the part to be deformed and cannot be regulated accurately. Therefore, the control of forming force in this paper mainly focuses on blank holder force and counter punch force. They continuously changes according to the blanking stroke. When applying a variation force during the fine blanking process, on the one hand, it can reduce the pressure on the mold in the early and middle stage; on the other hand, the peak forming force time during the loading process is shortened, which reduces the energy consumption of the equipment.

In this paper, a 2D finite element simulation model for fine blanking was established. The influence of forming force on parts was explored, and the mechanism of force variation fine blanking was proposed. Based on a large amount of simulation data, a neural network model was established with two forming force values as input and the length of clean cutting surface as output. The genetic algorithm was used to optimize the neural network model. The die load and the length of the clean cutting surface are set as the two optimization goals for multi-objective optimization. The final result was verified by simulation to get higher quality parts with longer tool life.

2 Fine-blanking Finite Element Simulation

2.1 Material model

Titanium alloy is a high-strength material with a wide range of applications ^[15]. Therefore, TC4 titanium alloys were selected as the material in the simulation in this paper.

In this simulation, the J-C model ^[16] was selected as the material model, and the Oyane criterion was selected as the material fracture criterion ^[17, 18]. The parameters of the J-C constitutive model were obtained as shown in Eq.1 by curve fitting that got after the tensile test (Fig.1a). Oyane criterion considers the influence of hydrostatic stress on material fracture, which is in line with the characteristics of fine blanking using hydrostatic stress to improve material fracture resistance. So Oyane fracture criterion is widely used in fine blanking. The parameters of Oyane fracture criterion can be determined by combining experiment and simulation methods ^[19]. Considering the limited space of this paper, this paper did not show this research process detailedly. Through the tensile tests of the TC4 billet with different stress triaxiality (Fig.1b), the parameters of Oyane fracture were obtained and shown in Eq.2.

$$\sigma = (969.9 + 1012.3\varepsilon^{0.59}) \left(1 + 0.01 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \quad (1)$$

$$0.7 = \int_0^{\bar{\varepsilon}^f} (1 + 3.2\eta) d\bar{\varepsilon}_p \quad (2)$$

2.2 Finite element simulation model

In this paper, DEFORM software was used to analyze the fine blanking process, and a finite element model was established for simulation analysis. In order to explore the principle of force variation fine blanking deformation, this paper selected cylindrical parts for analysis. The diameter of the parts is 20mm and the thickness is 4mm. Since the part is axisymmetric, a 2D finite element model was used for analysis according to its structural characteristics ^[20]. The schematic diagram of the model is shown in Fig. 2, and the parameters of the finite element model are shown in Table 1. In the fine blanking process, the material often begins to fracture at the edge of the die, so the acquisition node of mechanical parameters was selected here.

Table 1 Important parameters of the finite element simulation

Parameter	Value
Die diameter	20mm
Rounded radius of die	0.5mm
Punch diameter	19.98mm
Rounded radius of punch	0.01mm
V-ring height	0.6mm
Friction coefficient	$\mu = 0.1$
Blanking speed	5mm/s

In the process of finite element simulation, the forming force changes mainly around the calculated value of empirical formula. According to the empirical formula, the blank holder force is about 130kN and the counter punch force is about 60kN. In order to analyze the influence of different forming forces on fine blanking, two sets of simulation tests were designed. The forming force settings in the experiment are shown in Table 2.

Table 2 Finite element simulation design table

The first group			The second group		
Serial number	Blank holder force/kN	Counter punch force/kN	Serial number	Blank holder force/kN	Counter punch force/kN
1	72	48	6	120	24
2	96		7		48
3	120		8		72
4	144		9		96
5	168		10		120

3 The Influence Of Forming Force Change On Fine Blanking

Figure 3 shows the effect of the forming force on the length of the clean cutting surface and the die load. It can be seen from these curves that the higher the forming force is, the longer the length of the clean cutting surface of the parts is. However, the effect of the forming force on the length of clean cutting surface is weakened with the forming force increasing. At the same time, the improvement of forming force will bring higher load to the mold as shown in Fig. 4.

Taking the point marked with the red circle in Fig. 3 as an example, this point represents that the proportion of clean cutting surface of the part will occupy 67% of the part thickness when the counter

punch force is maintained at 48kN and the blank holder force is maintained at 96kN. Based on this, the length of the clean cutting surface can be determined by two forming forces. Conversely, based on the clean cutting surface and a certain forming force, the minimum value of another forming force can also be determined.

According to this analysis, each data point in Fig. 3 can be regarded as the critical state of material fracture under the forming force. When the forming force is not enough to maintain the triaxial hydrostatic stress state of the material, the micro cracks expand and combine, and the material breaks obviously. This is the critical state of the material. Therefore, one idea can be put forward. In the forming process, if the forming force is increased before the critical state of material fracture, whether it can obtain the same effect as maintaining high forming force during the whole process or not? In order to explore this thought, this paper carried out a finite element simulation according to the blank holder force loading curve shown in Fig. 5. In this simulation, the blank holder force changes according to the loading curve, and the counter punch force remains unchanged at 48kN.

Loading curve of blank holder force in Fig. 5 is designed from Fig. 3. Take the curve of force 4 in Fig. 5 and the points marked in Fig. 3 for example, the blank holder force in blanking stroke less than 60% is designed to be smaller. (After a short blanking stroke, the material is about to break.) When the blanking stroke exceeds 60%, the blank holder force value reaches 96kN and remains until the end of blanking. And the rest of the curve goes like that. The simulation results are shown in Table 3.

Table 3
Clean cutting surface ratio contrast

	Force 1	Force 2	Force 3	Force 4
Force variation loading	80.4%	76.6%	71.0%	65.4%
Constant force loading	81.0%	77.1%	70.7%	65.3%

As shown in Table 3, the finite element simulation results are basically the same when the variable blank holder force was used for loading, compared with the constant loading with high forming force. In the fine blanking process, the same effect can be achieved without the need to maintain a high finishing force throughout the whole process.

4 Neural Network And Genetic Algorithm Optimization Process

4.1 Neural network modeling

In this paper, a BP neural network model was established through the MATLAB platform. The structure diagram of the neural network model is shown in Fig. 6. The input layer of the neural network mainly involves two parameters. One is the blank holder force and the other is the counter punch force. In the process of modeling and optimization, it is necessary to find the optimal loading curve of blank holder

force and counter punch force, so both forming forces change with the blanking stroke. In the simulation, this paper divides the blanking process into three stages according to the time: the early stage, the middle stage and the ending stage. Each stage is given a forming force value, and the schematic diagram of final loading curve is shown in Fig. 7. For high strength and low plastic materials, the proportion of clean cutting surface is generally difficult to exceed 90%. If the forming force continues to be regulated at this time, a great force will be required. Therefore, in the last 10% of the blanking stroke, the forming force will remain the same as the value of the previous stage. Each forming force value represents an input in the neural network. Therefore, although the input variable only involves two forming forces, there are 6 variables, and each variable represents a forming force value, as shown in Fig. 7. The hidden layer has only one layer, the number of neurons is 12, and the number of neurons in the output layer is 1, which represents the length of the clean cutting surface^[21].

In order to make the data of the neural network accurate enough, the neural network should be trained with a large number of samples before obtaining the relationship between the two forming force and the clean cutting surface of the fine-blanking part. As the punching stroke progresses, the forming force value should continue to increase, so the force variation finite element simulation is arranged according to the law. Part of the finite element simulation arrangement table is shown in Table 4.

A total of 100 sets of finite element simulation data were set as the basic data for neural network modeling in this paper. At the same time, 75 sets of data were randomly selected from the basic data as the training set and 25 sets as the test set. After determining the structure of the BP neural network and analyzing the training results of it, it was finally determined that the learning function of the BP neural network adopts 'trainlm'. Through the analysis of Fig. 3, it can be known that when the blank holder force and the counter punch force reach a certain value, the effect of forming force on the length of clean cutting surface is weakened. Therefore, when setting up the simulation, the upper limit of the two forming forces, namely the blank holder force and the counter punch force, are designed to not exceed 180kN and 120kN, respectively. The final training result of the neural network is shown in Fig. 7.

Table 4
Finite element Simulation arrangement of blanking under force variation (selected)

Blanking stroke percentage	0-30%	30-60%	60%-90%		0-30%	30-60%	60%-90%
Blank holder force(kN)	0	0	0	Counter punch force(kN)	0	0	0
	180	180	180		96	96	96
	40	180	180		24	96	96
	40	40	40		24	24	24
	40	40	100		24	24	24
	40	40	180		24	24	24
	40	100	100		24	24	24
	40	100	180		24	24	24
	40	180	180		24	24	24
	100	100	100		24	24	24
	100	100	180		24	24	24
	100	180	180		24	24	24
	180	180	180		24	24	24
	40	40	40		24	24	60
	40	40	100		24	24	60
	40	40	180		24	24	60
	40	100	100		24	24	60
	40	100	180		24	24	60
	40	180	180		24	24	60

As shown in Fig. 7, it can be seen from the analysis of the prediction results of the neural network model that the prediction results of the neural network are very close to the results of the finite element simulation. Among them, the value of goodness of fit representing the accuracy of curve fitting reached 0.98, which proves that the accuracy of the neural network model is very high and can play a role in replacing the finite element simulation results.

4.2 Genetic algorithm optimization process

In the process of optimizing, it is necessary to use multi-objective optimization to optimize the clean cutting surface of parts and manufacture cost. Different from the single-objective optimization problem, the sub-objectives in multi-objective optimization are often contradictory ^[22]. Obviously, in the process of

optimizing, the lowest die load and the best quality for cutting surface cannot be achieved at the same time. Therefore, in this process, we need to find the Pareto optimal solution for this problem.

First, the initial population is randomly coded in a given range in the form of real number coding. The initial population is designed to be 100, the number of iterations is designed to be 200, the crossover probability is 0.9, the mutation probability is 0.05, and the number of optimization targets is 2. The first optimization goal is the clean cutting surface length S_1 of the part, which represents the quality of the fine blanking forming process. The other optimization goal is the sum of the numerical values of the two forming forces S_2 during the three stages, as shown in Eq. 3. This optimization goal represents the die load and the damage to the mold during fine blanking process. The objective function value of each individual through the BP neural network is calculated and graded. Then the non-inferior solution that meets the requirements is found and kept. If the set requirements are not met, continue with a series of genetic operator operations such as selection, crossover, mutation, etc. The feasible solutions that meet the conditions can be found finally until all Pareto solutions that meet the requirements are calculated. The final Pareto optimal solution is shown in Fig. 9.

$$S_2 = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 \quad (3)$$

It can be seen from Fig. 9 that the length of the clean cutting surface and the consumption of the forming force increase synergistically. At the same time, when the forming force increases to a certain extent, the growth of the length of the clean cutting surface has been extremely slow, and it is less efficient to continue to increase the forming force. Each data point obtained in the Fig. 9 (a) represents the optimal solution under each clean cutting surface calculated by genetic algorithm. Seven sets of data are selected from the Pareto optimal solution and compared with high forming force constant loading. Among them, the constant loading of maximum forming force means that the maximum forming force in the force variation process is used for simulation during the whole fine blanking process. The constant loading of the average force means that the value obtained by averaging the sum of the forming forces in the force variation process maintains a constant loading during the entire stroke for simulations. The result comparison is shown in Table 5.

Table 5
Comparison between prediction results and simulation results

Loading route						Result		
Blank holder force			Counter punch force			Force variation loading	Maximum force constant loading	Average force constant loading
0-30%	30-60%	60-90%	0-30%	30-60%	60-90%			
59.59	98	186.81	34.22	69.57	100	90.25%	90.50%	65.09%
57.76	95	188	39.67	67.66	99.98	90.50%	90.75%	66.20%
53.51	95.85	188	34.11	71.92	100	90.00%	91.25%	65.75%
58.89	94.85	188	34.18	74.89	109.85	89.75%	91.00%	66.65%
55.21	93.52	188	38.09	69.49	110	90.75%	91.75%	66.48%
52.39	92.9	187.25	42.35	67.99	109.64	90.75%	91.75%	66.32%
57.68	83.75	188	38.78	68.43	109.96	91.25%	92.00%	67.03%

It can be seen from the data in Table 5 that the quality of parts obtained by force variation process is similar to that obtained by constant loading of maximum force. And it is also much higher than that obtained by constant loading of average force. Several sets of Pareto optimal strategies gained through optimization are consistent with the conclusions got in the previous analysis in this paper. It does not need excessive forming force in the early stage, so the forming force value in the early and middle stage of the optimal solution is generally low. The forming force only needs to gradually increase, but does not need to keep at a high level throughout the whole process. The force variation can be used to obtain a higher part quality at a lower die load.

5 Result And Discussion

The criterion used in the analysis of fracture in this paper is Oyane criterion. In this criterion, there are three main factors affecting the fracture. They are equivalent stress, equivalent strain and hydrostatic stress. This paper selects the equivalent stress and equivalent strain data in the simulation to do the analysis. The data acquisition node is selected at the edge of the die as shown in Fig. 2. And three sets of simulations with obvious difference are shown in Table 6. From Fig. 10, the numerical value and changing trend of the equivalent stress and the equivalent strain at the edge of the die in these simulations are almost the same. Only when the material has fractured obviously, the equivalent strain data in these simulations begin to be different. The equivalent stress and equivalent strain of the material during the entire forming process are only related to the properties of the material and the punch stroke.

Table 6
Forming force in three groups of simulations

	Blank holder force(kN)	Counter punch force(kN)
Process 3	180	72
Process 2	150	48
Process 1	120	96

As shown in Fig. 11, there are three forces applied during the fine blanking process, namely the main blanking force, the blank holder force, and the counter punch force. From the perspective of the mold structure, the blank holder force and the counter punch force cannot cause the parts to have obvious plastic deformation. The equivalent stress is directly related to the plastic state, so the equivalent stress and equivalent strain will not be significantly affected when the forming force changes in a certain range.

As shown in Fig. 12, the hydrostatic stress at the cutting edge of the die and the change of damage value are counted. In the finite element simulation, the hydrostatic stress remained in the state of compressive stress in the early stage, and began to increase sharply in the ending stage. This is because in the early stage of fine blanking, the deformation of the material is almost all concentrated in a narrow area, so the hydrostatic stress state can be maintained without high forming force. At this time, the material deformation degree is also small, and the stress triaxiality increases little. The cavity-type damage inside the material is not obvious. In the middle and ending stage of fine blanking, the ratio of blanking clearance and die clearance to the thickness of sheet not yet blanked continues to expand. At this time, the area of tensile stress in the deformation zone continues to expand, and the micro-holes and micro-cracks continue to expand.

In summary, although the forming force has promoting effect on the growth of clean cutting surface, the effect in the early and middle stage of the blanking stroke is limited. With the punch stroke increasing, namely at the middle and ending stage, the thickness of the un-deformed sheet becoming thinner and the risk of cracking will be greatly increased. At this time, the influence of forming force on the cutting surface quality is continuously deepened. Therefore, by configuring the value of forming force, better cutting surface quality can be obtained with longer tool life.

In order to verify the effect on the length of the clean cutting surface by force variation fine-blanking, experiments were carried out on a hydraulic servo fine-blanking press, which the blank holder force and counter punch force can be servo controlled. The material for the experiment is TC4 alloy, and the part thickness is 4mm. The parts fabricated by the force variation loading are compared with that processed by the average force constant loading. According to the model obtained before, for the loading condition of force variation the blank holder force is 81KN in the early stage, 165KN in the middle stage, 223KN in the late stage, and the counter punch force is 42KN in the early stage, 68KN in the middle stage and 110KN in the late stage. For the loading condition of average force constant load, all process force values are calculated as mentioned before. The blank holder force and counter punch force for this part are

190KN and 80KN respectively. The comparison chart is shown in Fig. 13. When the parts are processed by the force variation loading, the length of clean cutting surfaces are about 3.7mm. The proportion of clean cutting surface reached over 90%. However, the parts processed by the constant loading of the average force have poor cutting surface quality. It is only 2mm in length, and quickly turned into a fracture zone. It is proved by experiment that force variation fine blanking can get longer clean cutting surface with lower die load.

6 Conclusion

(1) The variation trend of equivalent stress and equivalent strain is only affected by the material and blanking stroke. It is determined that the forming force mainly influences the length of the clean cutting surface by influencing the hydrostatic stress.

(2) The optimal processing curve of force variation fine blanking process was obtained through neural network and genetic algorithm. The optimal loading curve of forming force should be kept in a low level in the early stage of the blanking stroke, and increased gradually in the middle and ending stage.

(3) It is proved by experiment that force variation fine blanking can get longer clean cutting surface with lower die load. Using the force variation loading, higher quality for clean cutting surface can be obtained with longer tool life.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish:

All the authors have reached agreement for publication.

Authors Contributions:

Han Chen was responsible for the reading and induction of all literature; Yanxiong Liu and Huajie Mao were in charge of the whole trial; Kaisheng Ji were engaged in literature collection. All authors read and approved the final manuscript.

Funding:

Supports from the National Key R&D Program of China (No. 2020YFA0714900).

Competing Interests:

The authors declare no competing financial interests.

Availability of data and materials:

Our paper belong to a critical review. All data have been confirmed by experiments and simulations

Acknowledgements

The authors are grateful for the financial supports from the National Key R&D Program of China (No. 2020YFA0714900).

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Figures

Figure 1

The sample and result curve used to establish the material model: (a) the tensile test sample diagram and the true stress-strain curve (b) the Oyane criterion tensile test sample and the stress triaxiality value of the sample

Figure 2

Schematic diagram of finite element model

Figure 3

Change of clean cutting surface of fine blanking parts when forming force are changed

Figure 4

Influence of forming force changes on die load: (a) Changes of die load when blank holder

Figure 5

Load curve of blank holder force under force variation

Figure 6

Neural network model structure of fine blanking load process

Figure 7

Schematic diagram of forming force variation loading

Figure 8

Comparison between network prediction results and finite element results

Figure 9

Pareto front and load route: (a) Pareto front (b) The loading route represented by the points on the curve

Figure 10

Equivalent stress and strain data of three sets of simulations: (a) The equivalent stress changes (b) the equivalent strain changes

Figure 13

Comparison between the process of constant average force load and force variation load