The Cutting Force Simulation of 30CrMnSiA Based on AdvantEdge 2D Broaching

Zheng Hu¹, Wanhao Zhang¹, Xin Li² and Hanjun Gao³*

¹Science and Technology on Vehicle Transmission Laboratory, China North Vehicle Research Institute, Beijing, 100072, China;
²State Key Laboratory of Virtual Reality Technology and Systems, School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China;
³Corresponding author: Gao Hanjun hjgao@buaa.edu.cn

Abstract. 30CrMnSiA alloy steel is a kind of medium carbon quenched and tempered structural steel commonly used in machinery manufacturing industry, which has superior comprehensive mechanical and technological properties. In view of the great difficulty in solving the cutting process of metal by analytical method, this paper simulates the broaching process of 30CrMnSiA by using AdvantEdge software, and studies the influence of cutting parameters, tool geometry parameters, heat exchange coefficient of coolant and other factors on the cutting force. The results show that the cutting force increases with the increase of cutting width, cutting thickness, friction coefficient between tool and chip, and cutting edge radius, while decreases with the increase of relief angle. The cutting force decreases slightly with increasing of rake angle, and it almost does not change with the increase of cutting speed, coating thickness and the heat exchange coefficient of coolant.

1. Introduction

30CrMnSiA alloy steel is a kind of medium carbon quenched and tempered structural steel commonly used in the machinery manufacturing industry. It has the characteristics of high strength, toughness, hardenability, good fatigue resistance, and superior comprehensive mechanical and technological properties, so it is widely used in aviation, aerospace, automobile, machine tool and other industries [1, 2]. However, 30CrMnSiA alloy steel is accompanied by high temperature, high pressure, high strain rate, thermal strain and phase transformation during the cutting process, so it is difficult to analyse the cutting process by analytical method [3]. With the rapid development of computer technology, the cutting process can be simulated reliably, and the required parameters such as cutting force, cutting heat, residual stress, surface roughness can be obtained by using finite element analysis software.

The cutting force has a great influence on tool wear, surface integrity and fatigue life of machined parts, and its value depends on the interaction of various factors such as workpiece material, tool geometric parameters and cutting parameters [4]. In order to provide more accurate guidance for actual parts processing, scholars have carried out a lot of work to study the cutting force generated in the cutting process.

Liao et al. [5] obtained the Johnson-Cook model parameters of the 7050 aluminium alloy through the Hopkinson bar impact test. The three elements of cutting were optimized with the aim of cutting force and surface machining quality in AdvantEdge. Similarly, Han et al. [6] designed the GH4698 milling experiment through the Taguchi Method, and used the grey correlation analysis method to
optimize the milling parameters (such as cutting speed, cutting depth and feed per tooth) with the goal of cutting force, cutting temperature and material removal rate. Finally, the optimized parameters were obtained and verified by experiments. Yang et al. [7] and Liu et al. [8] studied the large feed milling process and three dimensional milling process using carbide coated end mill of Ti6Al4V respectively. They analysed the influence of cutting parameters such as feed per tooth, cutting speed, axial cutting depth and radial cutting depth on cutting force and cutting temperature, and got some similar results. Li et al. [9] studied the influence of cutting parameters on the cutting force of titanium alloy Ti6242 in turning process. The quadratic response surface regression mathematical model of the main cutting force was established and verified by experiments. The results show that the main cutting force decreases slowly with the increase of cutting speed, while increases significantly with the increase of feed rate and cutting depth.

Yang et al. [10] used orthogonal test method to study the influence of cutting parameters and tool geometry parameters on cutting force in high speed turning of GH4169 by Deform 3D simulation software, and established the empirical formula of cutting force. The parameter that has the most influence on the cutting force is the cutting depth, followed by the feed rate and the rake angle, and finally the tool nose radius. Sharman et al. [11] studied the influence of different tool materials, geometric dimensions, wear degree and operation parameters on the surface integrity of Inconel 718. The results show that the cutting of worn tools results in large microstructure deformation, microhardness change and high surface tensile stress, which has the greatest impact on the surface integrity. Similar results can be seen in the research of Yao [12]. Liu et al. [13] simulated the turning process of Ti6Al4V under dry cutting, ordinary cooling and high pressure cooling environment, studied the influence of the cutting environment on the cutting force and cutting temperature, and obtained the distribution of residual stress at different depths. Chen et al. [14] tested the milling force, milling temperature and tool wear of TC4 with deep-feed under liquid nitrogen cooling. They found that when milling TC4 with high cutting speed and feed per tooth, using liquid nitrogen cooling can reduce cutting force and cutting temperature more effectively than using emulsion, and it can extend tool life more effectively than using low temperature cold air cooling.

It can be seen that many achievements of cutting force and its effect in the cutting process have been achieved at the aspects of machining technology, cutting parameters, tool geometric parameters, tool wear, cooling and lubrication. However, there are not many researches on the broaching process of 30CrMnSiA alloy steel. In this paper, the AdvantEdge finite element simulation software is applied to simulate the 2D broaching process of 30CrMnSiA alloy steel, and the influence of various factors in broaching process on the cutting force is studied, which has a certain guiding significance for the processing parameters optimization and surface integrity control of 30CrMnSiA alloy steel parts.

2. Method

The two-dimensional broaching model is selected in the AdvantEdge software. Geometric model and friction model are given in the default form. The Johnson-Cook constitutive model (i.e. J-C constitutive model, including strain hardening effect, strain rate strengthening effect and thermal softening effect) is applied to describe the stress-strain relationship. Its form is simple and the parameters are few, so it is a common constitutive model in metal cutting deformation, especially under the condition of large strain, large strain rate and high temperature. The constitutive equation is as follows:

$$\sigma_{flow} = \left[ A + B\varepsilon_{dff}^n \right] \left[ 1 + \ln \dot{\varepsilon}^* \right] \left[ 1 - T^* m/3 \right]$$  \hspace{1cm} (1)

where $\sigma_{flow}$ is Mises flow stress; $\varepsilon_{dff}$ is effective plastic strain; $\dot{\varepsilon}^*$ is dimensionless equivalent plastic strain rate; $T^*$ is uniform temperature, recorded as $T^* = \left( T - T_0 \right) / \left( T_{m} - T_0 \right)$; $T_0$ is room temperature and takes 20℃; $T_m$ is the melting point; $A$ is the yield strength of material under quasi-static state; $B$ is the strain...
The hardening constant; \(n\) is the strain rate hardening index; \(C\) is the strain rate hardening coefficient; and \(m\) is the thermal softening index. The J-C constitutive model parameters and basic physical properties of 30CrMnSiA are shown in the table below\(^{[3,15]}\):

| Table 1 the constitutive parameters of 30CrMnSiA |
|-----------------------------------------------|
| A(MPa) | B(MPa) | \(n\) | \(C\) | \(m\) | \(e_0^{*}\) (1/s) |
|-------|-------|------|------|------|----------------|
| 525   | 101   | 0.081| 0.1739| 1.635| 5×10^{-4}     |

| Table 2 the basic physical parameters of 30CrMnSiA |
|-----------------------------------------------|
| Elastic Modulus (GPa) | Poisson’s ratio(\(\mu\)) | Density (kg/m\(^3\)) | Melting point (\(^\circ\)C) |
|----------------------|-------------------------|-----------------|---------------------|
| 201                  | 0.3                     | 7810            | 1527                |

| Table 3 thermophysical parameters of 30CrMnSiA |
|-----------------------------------------------|
| Temperature (\(^\circ\)C) | Specific heat (J/(kg \(^\circ\)C)) | Thermal conductivity (W/(m \(^\circ\)C)) | Thermal expansion coefficient (10\(^{-6}\)\(^\circ\)C\(^{-1}\)) |
|-----------------------------|-------------------------------------|------------------------------------------|-------------------------|
| 20                          | 473.1                               | 48.15                                    | 11.00                   |
| 100                         | 519.1                               | 46.47                                    | 11.59                   |
| 200                         | 581.9                               | 41.45                                    | 12.32                   |
| 300                         | 644.7                               | 38.1                                     | 13.09                   |
| 400                         | 699.1                               | 38.1                                     | 13.71                   |
| 500                         | 766.1                               | 35.17                                    | 14.18                   |
| 600                         | 841.5                               |                                           | 14.46                   |

The material of cutting tool is high-speed steel W6Mo5Cr4V2Co5 with a TiN coating, and the tool is meshed (the minimum and maximum element size are 0.02mm and 0.1mm, respectively). Fix the bottom area of the workpiece, set the initial temperature of the tool, workpiece and coolant as 20\(^\circ\)C, and use the immersion cooling medium. The immersion cooling means that all the exposed surfaces of tool and workpiece have thermal convection, except for the bottom area of the workpiece and the surface with constant temperature. The diagrammatic sketch of thermal convection is shown in b) of Figure.1.

In order to fully study the influence of various parameters on cutting force, the single factor analysis method is adopted. Under the condition that other factors are identical, the finite element simulation of broaching is carried out at different levels of different factors (including cutting width, cutting thickness, cutting speed, friction coefficient, heat exchange coefficient, rake angle, relief angle, cutting edge radius, coating thickness, etc.) respectively. The parameter settings are shown in Figure. 1. The stable value of cutting force could be obtained from result file for analysis.
Figures 1 shows the parameter settings of AdvantEdge.

3. Results and discussion

Some typical simulation results are shown in Figure 2, including the temperature distribution, Mises stress nephogram and the residual stress at different depths along the cutting direction. It can be seen from the results that the temperature and Mises stress at the cutting position are the highest, which can reach about 580℃, 1000MPa respectively, and then the value gradually decreases towards the surrounding area. There is a compressive stress of about 100MPa on the surface of the workpiece, and then it decreases along the depth direction until it becomes tensile stress, which reaches the maximum value of 30MPa near the position of 100 μm, and finally decreases to 0 near the position of 400 μm.

Figure 3 shows the typical curve of cutting force in the cutting process: the cutting force increases rapidly when the cutting tool starts to work, and then its value tends to be stable and fluctuates steadily. Among them, Force-x is the tangential force, which is consistent with the speed direction. It is the main basis for designing machine tool and selecting cutting parameters. Force-y is the radial force, which affects the machining accuracy and surface roughness of workpiece. The tangential force is mainly analyzed here. [16]

The results show that the cutting force increases with the increase of cutting width, cutting
thickness, friction coefficient between tool and chip, cutting edge radius, while decreases with the increase of relief angle. The cutting force decreases slightly with increasing of rake angle, and it almost does not change with the increase of cutting speed, coating thickness and the heat exchange coefficient of coolant.

Figure 2 the simulation results of temperature, Mises stress and residual stress

Figure 3 the curve of cutting force, a) cutting force in initial state; b) cutting force after fitting
Figure 4: The influence of cutting parameters on cutting force.

Figure 5: The influence of tool parameters on cutting force, a) curve of cutting force with rake angle; b) curve of cutting force with relief angle; c) curve of cutting force with blunt radius; d) curve of cutting force with coating thickness.
Figure. 6 the influence of other factors on cutting force, a) curve of cutting force with friction coefficient; b) curve of cutting force with heat exchange coefficient

With the increase of cutting width and cutting thickness, the effective contact area between the tool and workpiece becomes larger, so that the deformation and friction, as well as the cutting force, increase. The influence of cutting speed on cutting force mainly depends on the strain hardening and thermal softening of the material: when the workpiece is being cut, the surface hardens and the hardness increases, resulting in the increase of the cutting force; while the heat generated in the cutting process is easy to soften the material, which will reduce the hardness and strength, so the cutting force decreases. From the curve of cutting force with cutting speed, it can be seen that in the broaching process of 30CrMnSiA alloy steel, the tangential force changes very little, while the radial force increases with the increase of cutting speed, which is the interaction result of strain hardening and thermal softening.

With the increase of rake angle, the cutting tool becomes sharper, which reduces the extrusion on the workpiece and the deformation of chip, so the cutting force tends to decrease. With the increase of the relief angle, the friction between the tool’s rear face and the machined surface decreases, as well as the cutting force, which improves the machined surface quality and the tool’s life. When the cutting edge radius increases, the cutting edge of blunt circle increases, the average main deflection angle decreases, resulting the increase of cutting force. The influence of cooling water on the cutting force is small, while the cutting oil with strong lubricating effect can reduce the friction to decrease the cutting force, even reduce the plastic deformation of the metal. [16]

4. Conclusion
In this paper, the broaching process of 30CrMnSiA alloy steel is simulated by AdvantEdge software. Based on Johnson-Cook constitutive model, the parameters of 30CrMnSiA are given, and the boundary conditions are set. Then the broaching finite element simulation is carried out at different levels of different factors. The cutting force are analysed and the conclusions obtained are as follows:

Within the research level of this paper, the cutting force produced in the broaching process of 30CrMnSiA increases with the increase of cutting width, cutting thickness, friction coefficient between tool and chip, cutting edge radius, while decreases with the increase of relief angle. The cutting force decreases slightly with increasing of rake angle, and it almost does not change with the increase of cutting speed, coating thickness and the heat exchange coefficient of coolant.

If a smaller cutting force is wanted to reduce the machining deformation, we can reduce the cutting width, cutting thickness, friction coefficient between the tool and chip, the radius of blunt circle, increase the relief angle, and use the coolant with lubricating effect in a proper range.
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