Computational Model for Impact-Resisting Critical Thickness of High-Speed Machine Outer Protective Plate

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Abstract. The blade or surface grinding blade of the hypervelocity grinding wheel may be damaged due to too high rotation rate of the spindle of the machine and then fly out. Its speed as a projectile may severely endanger the field persons. Critical thickness model of the protective plate of the high-speed machine is studied in this paper. For easy analysis, the shapes of the possible impact objects flying from the high-speed machine are simplified as sharp-nose model, ball-nose model and flat-nose model. Whose front ending shape to represent point, line and surface contacting. Impact analysis based on J-C model is performed for the low-carbon steel plate with different thicknesses in this paper. One critical thickness computational model for the protective plate of high-speed machine is established according to the damage characteristics of the thin plate to get relation among plate thickness and mass, shape and size and impact speed of impact object. The air cannon is used for impact test. The model accuracy is validated. This model can guide identification of the thickness of single-layer outer protective plate of a high-speed machine.

1. Introduction

Some hazardous factors such as splashing cuttings and high-speed flying tool or grinding wheel caused by accidental damage in high-speed cutting may exist (see Fig. 1), which will severely injure persons and even lead to death accidents, so the protective plate of the high-speed machine should resist certain impact damage and secure operators around the high-speed machine.

Now the impact characteristics of a thin plate are mainly studied in military, aerospace, earth and planetary physics field. The impact characteristics at a hypervelocity are focused (several km to tens of km per second) [1]. It is generally believed that the linear velocity of 150m per second is the dividing line between high speed and super high speed in machine tool. After the thin plate is impacted at a high speed, some debris cloud will be formed [2]. Zhang Yongqiang, Gai Fangfang, Liu Yingfang, at al respectively studied characteristics of debris cloud characters caused by the ball projectile, cylinder projectile and conical projectile [3-5]. Chi et al studied the debris cloud characteristics after the aluminum ball impacts 0.5mm and 1mm aluminum plate at a hypervelocity [6]. When the speed is lower, the thin plate will be torn and damaged. Rusinek et al studied penetration damage of low-carbon steel thin plate [7]. Gang Jingbo analyzed damage of the thin plate under action of the contact explosion load. The breach of the plated grillage shows the petal damage [8]. Du Zhipeng et al studied the model of the thin plate pedal damage under impact of a sharp-nose projectile, which can deduce the ballistic limit [9]. The damage styles of the thin plate are very different under
high-speed and hypervelocity impact. The outer protective thin plate of the high-speed machine is mainly damaged due to tearing instead of debris cloud.

![Image](image1.png)

**Figure 1.** Some tool accidents in high-speed machine

Based on research conclusion on the thin plate’s high-speed impact, researchers have proposed Whipple protective structure and multiple enhanced protective structures based on it and analyzed ballistic limit characteristics, including density-grade thin plate, sandwich cellular interlayer structure, corrugated sandwich protective structure, stainless steel mesh/aluminum plate protective structure, etc. The protective thin plate for hypervelocity impact is mainly made of the aluminum plate. Now the researched materials cover C/Si material, polyester plate, silk/epoxy/foam sandwich material, compound elastic materials, foam aluminum, porcelain aluminum plate, etc. Generally, these structures and materials are used for hypervelocity impact cases. Although they can be referred in machine protection, the protection speed is too high and the cost is too high, so they are not fully suitable for civil high-speed machine field.

This paper takes the boundary velocity 150m/s of super high-speed as the studying speed for high-speed machine protection. This speed is approximately equivalent to the projectile speed, so it is very dangerous for operators close to the machine. Existing single-layer ballistic limit computing equation is based on the hypervelocity impact research, including five relational model between single-layer plate and impact object such as Fish-Summers, Schmidt-Hoisapple, Rockwell, JSC and correction equation, the computing equation is complicated and the key materials such as aluminum alloy and 304 stainless steel are included. Now the high-speed machine protective plate is mainly made of Q235/SPCC. Thickness mainly depends on experiences. The supporting theory for thickness of impact-resisting critical protective plate is not provided. By analyzing impact resistance of the protective thin plate, one new simple and easy-to-calculate impact-resisting critical thickness model of the protective plate is established and theoretical support for design of the outer protective plate of the high-speed machine is available in this paper.

2. High-speed impact object model

Any impact object of the high-speed machine will contact the outer protective plate in a point, line and plane manner and the front impact will damage the plate much. The heavier 42g single grinding wheel in the measured CBN grinding wheel is used as the mass of the impact object. The end of the impact object is simplified as ball-nose, flat-nose and sharp-nose. Three impact objects are designed (refer to the figure 2). They are named as ball-nose projectile, flat-nose projectile and sharp-nose projectile according to the end characteristics to analyze protection characteristics of the protective plate under different impact objects.
3. Simulation model of high-speed impact

ABAQUS display mechanics analysis module is used for simulation in this paper. The impact object is set as the rigid body. The Johnson-Cook material failure model is used[23] to analyze the heat insulation instantaneous dynamics analysis in case of high-speed impact. The ultra-high line speed 150m/s[24] in the machine field is used as the impact speed. The common Q235 steel plate is used as the protective plate for protection analysis of the machine’s outer plate.

3.1. Impact performance of three impact objects with different shapes on one protective plate

Two-millimeter-thick Q235 steel plate is used as the protective steel plate. Shown as the figure 3, when the ball-nose projectile impacts the plate, the plate will be gradually deformed. The maximal impact force occurs at the maximal diameter to break the plate. The diameter of the broken chip is similar to the maximal diameter of the projectile body. The damaged hole edge of the plate shows slightly visible petal. When the flat-nose projectile impacts the plate, the surrounding shape edge will form the blanking effect and the round chip with the diameter as the projectile diameter will be directly extruded and chiseled, so the extrusion and chiseling damage occurs. When the sharp-nose projectile pierces through the protective plate, no materials fall off and it leads to petal piercing damage. When the protective plate is impacted by the sharp-nose projectile, the plate will be quickly damaged due to local stress concentration. With advance of the projectile, the initial stress wave will generated the circumferential and radial high tension stress in the plate. When the circumferential stress reaches the extreme stress, the cracking conditions are satisfied and some tenacious cracks will be generated. The cracks will continuously expand along the initial direction to form the bigger crack and finally form the petal damage.

By analyzing speed change curve of three objects before and after piercing through the protective plate (see the figure 4), when the ball-nose projectile, flat-nose projectile and sharp-nose projectile pierce through the protective plate, the speed loss is 33.7%, 62.4% and 31.8%. The time for full penetration is 0.2ms, 0.25ms and 0.3ms respectively. The speed loss of the flat-nose projectile reaches the maximum. The speed loss of the ball-nose projectile is similar to it of the sharp-nose projectile.
The speed reduction curve of the sharp-nose projectile and ball-nose projectile is similar to the sectional bus line of the head. The speed of the sharp-nose projectile will linearly reduce. The speed of the ball-nose projectile will reduce as a curve. The speed of the ball-nose projectile and sharp-nose projectile will change stably. The flat-nose speed experiences skip change, which may be caused by instantaneous cutting of the round chip. It will lead to different scraping between the section burr of the plate and flat-nose projectile. When the flat-nose projectile pierces through the plate, unstable friction resistance will lead to speed fluctuation. Based on above analysis, if the contact circumference between the impact object and protective plate is longer, it will significantly resist.

**Figure 4.** Speed change rule of different projectile impacts on 2mm protective plate

3.2. **Impact performance of three impact objects with different thicknesses**

Q235 plate is used and the proportional method is used to increase the plate thickness and analyze impact under different thicknesses.

3.2.1. **Impact performance of ball-nose projectile on protective plates with different thicknesses.** He increased thickness will significantly enhance damage resistance of the protective plate. Shown as the figure 5, when t is 2mm, the projectile will pierce through the plate. When t is 3mm, although the plate breaks, the impact-incurred broken chips do not fully separate from the protective plate, and the projectile does not pierce through the plate and rebound. When t is 4mm, the protective plate only has plastic deformation to form the tray concave, but it does not break and prevent against impact from the impact object. The thin plate damage under the high-speed projectile is similar to the stamping and flanging.

**Fig.5** Phenomena of ball-nose projectile impacts on different thickness protective plate

3.2.2. **Impact performance of flat-nose projectile on protective plates with different thicknesses**

Shown as the figure 6, when t is 2mm, the projectile will cut the plate and pierce through it. When t is 3mm, the plate surface suffers from slight damage and the plate will slightly rebound. The reverse speed is 2.58m/s. When t is 4mm, the plate is not fully damaged and bigger rebounding occurs to
prevent against impact of flat-nose projectile. When the thickness of the protective plate reaches 3mm, the plate can prevent against impact of the flat-nose projectile. The thin plate damage under the flat-nose projectile is very similar to cracking of the plate blanking.

(a) t=2mm                         (b) t=3mm                      (c) t=4mm

Figure 6. Phenomena of flat-nose projectile impacts on different thickness protective plate

3.2.3. Impact performance of sharp-nose projectile on protective plate with different thicknesses

For the impact characteristics of the sharp-nose projectile protective plates with different thicknesses, refer to the figure 7. When t is 2mm, the projectile will pierce through the protective plate. When t is 3 and 4mm, the front part of the plate will be broken by the tip of the projectile, but the projectile does not pierce through the plate. The piercing depth of the tip becomes smaller and smaller. For the protective plate, the impact object does not fly out from the protective plate, namely the protective plate can protect. Under the high-speed impact of the sharp-nose projectile, the thin plate damage is similar to it of the stamping and flanging.

(a) t=2mm                     (b) t=3mm                   (c) t=4mm

Figure 7. Phenomena of sharp-nose projectile impacts on different thickness protective plate

4. Analysis on protection model of single-layer protective plate

Based on the above analysis, the relational mode of related parameter of the impact object damage-protective plate can be established by referring the blanking pressure and flanging force computational model[25] of the impact stamp die (refer to the formula 1). The coefficient is a correction coefficient based on the actual factors, e.g. change of impact speed, change of impact object mass, etc.

\[
F = \begin{cases} 
   l = 2\pi \sqrt{2\tau x - x^2} & x \leq r, \text{Ball - nose projectile} \\
   l = \frac{2\pi x}{h} & x \leq h, \text{Sharp - nose projectile} \\
   l = 2\pi r & \text{Flat - nose projectile}
\end{cases}
\]

(1)

The shear-resisting strength \(\tau\) depends on the type and shape of the thin plate material. For easy calculation, generally the estimated shear-resisting strength \(\tau\) is taken as 80% of the strength limit \(\sigma_s\) of this material in the metal stamping technology, namely \(\tau = 0.8\sigma_s\). For easy analysis, the material strength limit replaces the shear-resisting strength in this paper. The formula (1) is transformed to the formula (2).
0.8 \sigma_t b F = \Delta T \tag{2}

With growth of the protective plate thickness, the protection capabilities will gradually increase. If the protective plate with \( t \) thickness can just resist the impact object to the speed zero, namely the impact object is blocked inside the protective plate and does not pierce it, the thickness of this protective plate is called as the critical thickness. With momentum conservation transformation, the formula 2 is transformed to the formula (3).

\[ F \cdot \Delta T = K \sigma_t \cdot \Delta T = m v_1 - m v_2 \tag{3} \]

The formula (3) can be further transformed to get the determination model of the critical thickness of the protective plate (refer to the equation 4), which is related to mass, speed and dimension of the impact object and the tensile strength of the protective plate.

\[ t_c = \frac{m v_1}{K \sigma_t \cdot \Delta T} \tag{4} \]

In this formula:
- \( F \) = Damage form of protective plate/N;
- \( \Delta T \) --time when the impact object switches from contact with the protective plate to separation from the protective plate (or be blocked inside the plate)/s;
- \( m \) = mass of impact object/kg;
- \( v_1 \) -- speed of impact object in case of contact with protective plate/ms/s;
- \( v_2 \) -- speed of impact object in case of separation from the protective plate (if it is blocked, the speed is 0)/m/s;
- \( k \) -- correction coefficient for actual conditions;
- \( K \) -- 0.8k;
- \( l \) -- contact perimeter of the impact objects with protective plate in case of impact of impact object/mm;
- \( t \) -- thickness of protective plate/mm;
- \( x \) -- moving distance since the elastic body contacts the protective plate/mm;
- \( h \) -- distance from the tip to the bottom/mm;
- \( \sigma_t \) -- tensile strength of material/Mpa;
- \( t_c \) -- critical thickness of protective plate.

5. Model validation
The impact object fails to pierce the Q235 protective plate in three impact for 3mm thick protective plate. The acting time with the whole protective plate is about 500\( \mu \)s. \( K \) value is calculated by using the final position of the elastic body and the contact perimeter of the protective plate in the model and the formula (3). For related values, refer to the table 1. The \( K \) values are approximate for three objects.

| Parameter name           | deceleration time (s) | Contact perimeter (m) | \( \sigma_t \) (Pa) | m(kg)  | V1 (m/s) | V2 (m/s) | K     |
|---------------------------|-----------------------|-----------------------|---------------------|--------|----------|----------|-------|
| Ball-nose projectile      | 550E-6                | 40.8E-3               | 410E6               | 42E-3  | 150      | 0        | 0.228 |
| sharp-nose projectile     | 490E-6                | 47.1E-3               | 410E6               | 42E-3  | 150      | 0        | 0.222 |
| flat-nose projectile      | 500E-6                | 47.1E-3               | 410E6               | 42E-3  | 150      | -2.58    | 0.221 |
The above simulation results show that the reaction time of the impact object and protective plate is within hundreds of microseconds. If the mean $K$ is 0.22 and the mean impact reaction time is 500μs, the formula (4) can be modified as formula (5):

$$t_r = \frac{909 \cdot mv_i}{l \sigma_p}$$

In this formula, $l$ is calculated by using the maximal contact perimeter of the impact object with the protective plate in case of impact. The formula (5) is used to compute critical thickness of the ball-nose projectile under different impact speed, which is compared with the thin plate thickness via impact simulation. The results show (refer to the figure 8) that all computed critical thicknesses resist penetration of the impact objects when $v_i \leq 340 \text{m/s}$. When the critical thickness is smaller, most protective plates will be pierced, so the formula (5) is feasible in calculation of the critical thickness of the protective thin plate of the high-speed machine. According to figure 8, the impact velocity of formula (5) is limited to $v_i \leq 340 \text{m/s}$.

![Figure 8](image)

**Figure 8.** The resistance of different thickness protective plate for different impact speed

By analyzing 3mm thick Q235 protective plate in the experiments, the air cannon is used to fire the ball-nose projectile (42g) and the impact rate measured by the laser velocimeter is 168m/s. The experimental results are shown as the figure 8. The ball-nose projectile is blocked inside the protective plate and does not pierce the plate. The simulation results show that the protective plate is pierced. When the protective plate reaches 3.32 mm critical thickness calculated in the formula (5), the protective plate is not pierced. Simulation ignores factors such as elastic plastic deformation and heat loss in the true environment, so the simulated critical plate thickness is higher than the true critical plate thickness under equal impact conditions, namely the plate thicknesses calculated by the critical thickness calculation model (refer to the formula (5)) has certain safety tolerance.

![Image](image)

(a) The ball-nose projectile is blocked inside the plate
6. Conclusions

The impact resistance performance of the protective plate of the high-speed machine and simulates impact process is analyzed by using J-C model in this paper. The simulation results show that the protective plate damage complies with the fourth strength theory under the high-speed impact in the machine field. The shape-specific energy is the key factor to lead to material’s yield damage. By combing the mechanical model in the plate stamping field, we deduce a new and easy-to-calculate critical thickness calculation model of the impact-resisting protective plate. The impact experiments show that the model results are reliable and have certain safety tolerance, so this model can be adopted as the theoretical support to identify the thickness of the protective plate of the high-speed machine.

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**Acknowledgments**

This work is supported by the Major Project of High-end CNC Machine Tools and Basic Manufacturing Equipment of China (2014ZX04011021), Project of Shaanxi Province(2016KTCQ01).