Development of a model for predicting the flash temperature during impact of titanium alloy

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Abstract
The use of light metals in mines is limited by the sparks and hot surfaces induced by mechanical friction and impact especially, hot surfaces which could ignite explosive atmospheres prior to the mechanical sparks. In view of this, the research on the collision hot surface is based on the simulation of the falling gravity hammer test. The change law of the collision temperature field with the impact conditions is obtained by numerical simulation. The mathematical model for calculating the maximum flash point temperature is derived. And proves that whether the flash temperature is related to the mass needs to consider the elastic-plastic deformation of the material itself. Only when the compressive stress reaches the extreme value or the material is ideal elastic-plastic material, the flash temperature is independent of the mass. In addition to the properties of materials, friction coefficient, relative velocity and normal load are the main factors affecting the compressive stress of impact. Thus, an important method can be obtained that controlling the coefficient of friction between the acting surfaces within a critical range by improving the processing accuracy of the material surfaces may ensure the safety of the hot surfaces generated by impact.

Keywords
Hot surfaces, flash temperature, frictional impact, titanium alloy, the falling gravity hammer test

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Introduction
With the rapid development of science and technology, energy saving and low consumption is an important direction in the development of structural materials. Replacing traditional steel materials with lightweight and high-strength materials as materials for mining machinery and equipment is one of the important ways to achieve this development. It is well known that light alloy materials are used in explosive gas environments, and frictional impact sparks are one of the most dangerous potential ignition sources.¹ The main factors affecting impact friction sparks are the nature of the material and the relative friction speed,²,³ if the impact friction material is determined, the critical speed can be set to limit the generation of impact friction sparks. A large number of standards and regulations check the spark safety of light alloy by setting test methods or limit the use conditions by setting critical speeds to control the generation of frictional impact sparks. While setting the critical speed is only a method to control the impact friction sparks as an effective ignition source and cannot guarantee the safety of the hot surface. Actually, prior to the occurrence of mechanical sparks,
hot surfaces are always developed. Hot surface is also one of the potential ignition sources of light alloys used in explosive atmospheres, so what are the main factors that make hot surface an effective ignition source of combustible gas, previous studies have shown that the maximum temperature of the hot surface is determined by the relative power density of friction rather than simply by the relative friction speed.4,5 Meyer’s research proves this, bronze, which is considered to be a sparkless material, still has the ability to ignite ignitable mixture. He also studies the frictional hot surfaces of different types of steel, which have no frictional sparks at the lower relative power density, but can also detonate combustible gases. Proust also studied the same problem. He measured the development of frictional thermal surfaces of high strength steel, medium strength steel, bronze, pure aluminum and quartz with loads of 0~5000 N and rotational speeds of 0.2~20 m/s. The results showed that: more than 80% of the energy generated by friction is transferred to the interior of the material by conduction, and the heat dissipation to the surrounding environment is only 10%~20%. The heat taken away in the form of debris or sparks is less than 1%, which can be ignored. The decisive factor for the temperature of hot surface is the heat conduction of the material. Similarly for friction, the calculation of critical friction power is not limited by the lower boundary of friction velocity, that is to say, the development of hot surface cannot be guaranteed by setting the lower boundary of friction velocity. He Pan6 studied the hot surfaces generated by friction contacts of titanium alloy and steel by combining experiments and numerical simulation, and build the titanium alloy friction temperature field calculation method. The introduction of simulation technology can show the complex friction temperature rise process completely7–9 and can obtain the process data that cannot be obtained by experiment, and is not limited by experimental conditions, can repeat the friction process many times, and adjust the data to analyze each influence factor one by one. For the study of hot surfaces generated by impact, the traditional falling gravity hammer test equipment is complex, heavy and the test cost is high. It is difficult to implement in the laboratory and needs to be tested by a professional testing organization because it is dangerous. So the researchers devised new experiments to replace the falling gravity hammer test. Hollander used springs with kinetic energy stored to push the hammer attached the sample at the bottom to impact test board then studied the hot surface and sparks produced by sample scraping test board. Proust developed a new device using a special “air driven cannon” to propel a projectile accurately onto an inclined target. This device is more convenient to measure the temperature rise at the point of impact. Although these devices improve the disadvantages of falling gravity hammer test devices, the tests are still only a verification of the results whether the hot surfaces and sparks can ignite ignitable mixture, and process data is still unable to obtain. In view of this, in this paper, a collision temperature test system is built by numerical simulation, which can accurately measure the temperature distribution and flash temperature of the collision friction surface. The accuracy of the simulation results was verified by theoretical calculations. The required experiment is simple, easy to operate, without explosion risk and the process data of the whole process of collision contact is easy to obtain.

The model

According to the national standard, the impact model established is shown in Figure 1(a). The tested sample TC4 (its size is shown in Figure 1(c)) is bonded under the spindle-shaped copper weight (Figure 1(b)) and falls freely from a height of 2m then impact with Q235A test board with an inclination angle of 55° at an initial velocity of 6.26 m/s. The location of collision contact point was the origin of the coordinate system, the direction perpendicular to the test board is the Y axis. The two axes parallel in the direction of the test board are X and Z axis, respectively (Figure 1(a)). The sample is TC4 titanium alloy with an elastic modulus of 110 GPa. The test board is made of Q235A steel, and its elastic modulus is 201 GPa. The elastic modulus of the test board is much higher than that of the sample, so it can be regarded as a collision between an arc plane with a radius of 5 mm and a rigid body plane.

The boundary conditions should be set to get a certain solution for the heat transfer problem. The inner surface of the sample and the lower surface of the test plate were in direct contact with the surrounding air, and there was convective heat transfer, which belong to the third type of boundary conditions. It could be expressed as equation:

\[ \lambda \left( \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z} \right) + h_{air} (T - T_f) = 0 \] (1)

where \( \lambda \) is the heat conduction coefficient of material, \( h_{air} \) is the surface heat transfer coefficient of the ambient air, \( T_f \) is the ambient temperature.

The collision contact area generates heat, and heat transfers heat to the sample and the test board respectively, which belongs to heat conduction and is the second boundary condition, where the boundary condition is:

\[ y = 10mm, \quad -k_1 \frac{\partial T}{\partial y} = Q \] (2)
where $Q$ is the collision friction heat, $k_1$ and $k_2$ is heat conduction coefficient of TC4 and Q235A, respectively.

Four faces around the test board and the upper side of the sample, the heat on these boundaries can be transferred freely, no heat conduction occurs in a short time, and the temperature is consistent with room temperature. These boundaries belong to the first type of boundary conditions:

$$T = T_0$$  \hspace{1cm} (4)

where $T_0$ is the surrounding temperature.

**Material parameters**

The tested sample is TC4 (Ti-6Al-4V) titanium alloy, the impact friction pair is Q235A steel (test board material is required in national standards, with size of $500 \text{mm} \times 230 \text{mm} \times 8 \text{mm}$) and the hammer is pure copper. It is not easy to produce impact friction sparks and will not interfere with the detection of samples. The physical parameters of each material are shown in Table 1.

**The meshing**

The interaction time between the specimen and the test board is very short, the contact time less than 0.001 s, the calculation time which is set to be 0.005 s is not long, so the overall meshing is used (Figure 2). A detailed analysis of the force and temperature field of the specimen is required, so the grids of sample and test board are relatively dense, the approximate global size of grid for board is 5, for sample is 2. The hammer does not interact with other specimens, only serves as a counterweight for the specimen, and does not need to consider its convergence problem, thus the mesh is sparse, but its irregular shape needs to be divided into areas for meshing. For the test board, total number of nodes are 22,302 and total number of elements are 14,500. The sample have 13,052 nodes and 10,920 elements. The type of the element is linear hexahedral element of type C3D8T. Because the mass of the hammer is different, its size is also different, the total number of elements and nodes of hammers of different sizes is not consistent.

**Analysis of simulation results**

**Cloud image analysis**

After the sample collides with the test plate, the temperature field and stress cloud diagram of the titanium alloy specimen are shown in Figures 3 and 4, respectively. The contact area is very small, it is a point contact, and the maximum of temperature and stress appear at the center of the contact area and gradually decrease from the center to the surrounding.

The hot surfaces generated by the impact are similar to them generated by the rotating friction, and are also produced by tangential friction. But when the material is plastically deformed, part of the hot surface temperature comes from the heat of plastic deformation. In order to facilitate the comparison of the maximum temperature difference of the hot surface when the impact and friction generate the same amount of heat, the parameters of the impact and friction are selected the same, that is, the same normal load $F_N$, tangential velocity $v_t$, surface friction coefficient $\mu$, and the same room temperature ($10^\circ C$). The normal loads of the friction system are 200, 300, 400, 500, 600, 700, and 800 N, respectively; the relative speed is selected as a higher speed of 0.69 m/s; then the corresponding weights of
the weights are 25, 37, 50, 62, 74, 87 and 100 kg, the collision speed between the sample and the steel plate is 0.84 m/s, and the contact stress and the highest flash temperature value of the two models under different load conditions are obtained (Table 2).

Regardless of the rotational friction model or the impact model, the contact stress basically increases linearly with the increase of load. For the same normal load and relative velocity, the contact stress of impact is much higher than that of friction contact stress.

The relationship between impact stress and weight of heavy hammer

In order to study the relationship between the impact stress and the weight of the hammer, assuming that the friction coefficient was not affected by the normal loads, the value is 0.1 (The effect of friction coefficient on temperature will be discussed in detail in part 2.4 of the text). The weight of the hammer is taken according to the test standard. Then under the action of different weights, the change of contact compressive stress at the center node of impact is shown in Figure 5. The abscissa is time, and the total simulation time is 0.005 s. It can be seen from the figure that the action time is extremely short, less than 0.001 s. Figure 5(a) shows the change of stress under the action of a weight of 10 kg, positive and negative stress means tensile stress or compressive stress. Negative value in this figure means compressive stress. During impact, the stress rapidly increases to the maximum value, and then the stress quickly decreases to close to zero, but there is a certain margin. This is due to the plastic deformation of the material and the stress does not return to zero after the impact. When the weight of the hammer is 60 kg (Figure 5(b)), the model with large impact force will vibrate and there will be multiple peaks, but it is still the instantaneous compressive stress of the impact that reaches the extreme point and then recovers. The

Table 1. Material performance parameters.

|             | Young's modulus (GPa) | Poisson's ratio | Density (kg/cm³) | Thermal conductivity (W/m·°C) | Specific heat (J/kg·°C) | Coefficient of thermal expansion (1/°C) |
|-------------|-----------------------|----------------|------------------|------------------------------|-------------------------|----------------------------------------|
| Cu          | 110                   | 0.34           | $8.9 \times 10^3$ | 377                          | 386                     | $1.7 \times 10^{-5}$                    |
| TC4         | 110                   | 0.34           | $4.5 \times 10^3$ | 7.955                        | 612                     | $8.6 \times 10^{-6}$                    |
| Q235A       | 201                   | 0.26           | $7.8 \times 10^3$ | 53                           | 490                     | $1.14 \times 10^{-5}$                   |

Figure 2. The mesh of model.

Figure 3. The temperature field cloud of impact with momentum of 375.6 kg m/s.

Figure 4. The stress cloud of impact with momentum of 375.6 kg m/s.
margin is slightly larger than the weight of 10 kg, indicating that the plastic deformation of the material is greater, the greater the applied load, the greater the plastic deformation of the material, and the higher the stress margin value.

Under the action of weights of different masses, the specific values of the maximum compressive stress are listed in Table 3. Using regression analysis method to study the relationship between the impact compressive stress and the mass of the weights, the quintic curve fits better (Figure 6), and the curve equation is as follows:

\[ P_y = 1.822 \times 10^{-7} m^5 - 3.194 \times 10^{-5} m^4 + 0.002104m^3 \\
- 0.06466m^2 + 0.9873m + 0.004141 \]  

where \( P_y \) is the impact compressive stress.

Through the fitting of the scatter points and the curve (Figure 6), it can be found that the quintic curve

**Table 2.** The hot surfaces temperature of friction mode and impact mode.

| Normal loads (N) | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|------------------|-----|-----|-----|-----|-----|-----|-----|
| The weight of the hammers (kg) | 25 | 37 | 50 | 62 | 74 | 87 | 100 |
| The contact compressive stress (MPa) | 50.7 | 74.0 | 99.1 | 123.3 | 148.4 | 177.8 | 200.4 |
| The impact contact stress (MPa) | 2344 | 2485 | 2654 | 2818 | 3070 | 3207 | 3352 |
| The temperature of hot surfaces generated by friction (°C) | 38.50 | 46.9 | 62.38 | 99.30 | 112.10 | 128.0 | 140.39 |
| The temperature of hot surfaces generated by impact (°C) | 33.65 | 37.71 | 46.41 | 50.89 | 54.33 | 61.85 | 68.24 |

**Table 3.** The simulation values of the impact compressive stress.

| The mass of the hammer (kg) | 10 | 20 | 30 | 40 | 50 | 60 |
|-----------------------------|----|----|----|----|----|----|
| The compressive stress (GPa) | 5.239 | 6.129 | 6.877 | 7.529 | 8.070 | 8.698 |

**Figure 5.** Stress-time curve: (a) 10 kg (b) 60 kg.

**Figure 6.** Regression analysis of impact compressive stress with different heavy hammers.
fits the scatter points very well, and there are no scattered points with large deviations.

Comparing the adjustment value and the mean square error value of the straight line, cubic curve and quintic curve, it can be seen (Table 4) that the degree of fit of the quintic curve is very high, so the linear model for determining the contact compressive stress and the mass of the weights is equation (5).

The relationship between impact flash temperature and mass of heavy hammer

The maximal flash temperature of impact rapidly increases to the extreme as the collision starts, then keeps steady (Figure 7). Because the time is short, whether heat dissipation is considered in the simulation has almost no effect on the temperature simulation results. With the increase of the mass of the heavy hammer, the maximum flash temperature of the hot surfaces continues to increase. The maximum flash temperature of the impact under the action of weights is shown in Table 5.

Similarly, the regression analysis method is used to study the relationship between the maximum flash temperature and the mass of hammers, and it is found that it satisfies the linear linear regression model, and the degree of fit between the straight line and the scattered point is very high (Figure 8).

According to the analysis, the linear model between the maximum flash temperature and the mass of the hammers is:

![Figure 7. Temperature-time curve.](image1)

![Figure 8. Regression analysis of the temperature of hot surfaces with different heavy hammers.](image2)
The relationship between the maximum flash temperature and friction coefficient

The influence of friction coefficient on temperature. The tangential friction coefficient of the collision between the sample and the test plate is not easy to measure, while the accuracy of the friction coefficient directly affects the accuracy of the simulation of temperature field. First, discuss the influence of the change of friction coefficient on the maximum flash temperature of sample. The coefficient of friction between metals is well known 0.1–1, while the friction coefficient between TC4 and Q235 measured by rotational friction at the condition of different loads and relative speeds is between 0.1 and 0.2. So the influence of the change of friction coefficient on the flash temperature is discussed specially. The friction coefficient between 0.1 and 1.0 is roughly studied, and between 0.1 and 0.2 is emphatically studied. The mass of the heavy hammer is 60 kg, the friction coefficient is 0.1–0.2. Table 6 shows the flash temperatures for every 0.01 increase in the coefficient of friction.

In the table, $\Delta T$ is the increase in temperature, $\Delta S$ is the increase in stress, $\delta T$ and $\delta S$ are the temperature increase ratio and the stress increase ratio, respectively:

$$\delta T = \frac{T_f - T_i}{T_i} \quad (7)$$
$$\delta S = \frac{S_f - S_i}{S_i} \quad (8)$$

It can be seen from the table that the friction coefficient is from 0.1 to 0.2, for every 0.01 increase, the stress increases slightly, and the growth rate gradually increases (Formula 7). At the same time, the temperature also slowly increases, the temperature growth rate slowly decreases (Formula 8), and the growth value does not change much. The average is 24.56, that is, every time the friction coefficient increases by 0.01, the maximum flash temperature increases about 24.56/0.01 = 2456°C. It can be seen that the accuracy of the friction coefficient has a great influence on the accuracy for simulation of flash temperature.

Variation of the maximal flash temperature with friction coefficient. Generally, the maximum friction coefficient of a metal surface does not exceed 1.0. According to the analysis of micro-tribology theory, the friction coefficient may be larger when the contact time is very short. Therefore, the friction coefficient is selected as 0.1–1.0, the simulation temperature and stress are listed in Table 7.

With the increase of the friction coefficient (Figure 9), the maximum flash temperature of the collision continues to increase. When the friction coefficient is 0–0.9, it basically increases linearly. When the friction coefficient is 0.9, the simulated temperature is the highest, and then the temperature decreased at the friction coefficient of 1.0. And the contact stress of collision (Figure

### Table 6. The friction coefficient effect on temperature and stress of sample.

| Friction coefficient | Flash temperature (°C) | $\Delta T$ | $\delta T$ (%) | Stress (MPa) | $\Delta S$ | $\delta S$ (%) |
|----------------------|------------------------|------------|---------------|--------------|------------|---------------|
| 0.10                 | 249.540                |            |               | 8698         |            |               |
| 0.11                 | 272.859                | 23.319     | 9.34          | 8764         | 66         | 0.76          |
| 0.12                 | 296.427                | 23.568     | 8.64          | 8829         | 65         | 0.74          |
| 0.13                 | 320.279                | 23.852     | 8.05          | 8897         | 68         | 0.77          |
| 0.14                 | 344.243                | 23.964     | 7.48          | 8966         | 69         | 0.78          |
| 0.15                 | 367.704                | 23.461     | 6.82          | 9037         | 71         | 0.79          |
| 0.16                 | 393.179                | 25.475     | 6.93          | 9109         | 72         | 0.80          |
| 0.17                 | 418.185                | 25.006     | 6.36          | 9182         | 73         | 0.80          |
| 0.18                 | 443.767                | 25.282     | 6.05          | 9257         | 75         | 0.80          |
| 0.19                 | 469.471                | 25.704     | 5.79          | 9333         | 76         | 0.82          |
| 0.20                 | 495.423                | 25.952     | 5.53          | 9411         | 78         | 0.84          |

### Table 7. The friction coefficient effect on temperature and stress of sample.

| Friction coefficient | Flash temperature (°C) | $\Delta T$ Stress (MPa) | $\delta T$ Stress (MPa) | $\Delta S$ Stress (MPa) |
|----------------------|------------------------|------------------------|-------------------------|-------------------------|
| 0.10                 | 249.540                | –                      | 8698                    | –                       |
| 0.20                 | 495.423                | 160.633                | 9411                    | 1014                    |
| 0.30                 | 761.873                | 266.45                 | 10,140                  | 729                     |
| 0.40                 | 1029.38                | 267.307                | 10,960                  | 820                     |
| 0.50                 | 1310.04                | 280.66                 | 11,990                  | 1030                    |
| 0.60                 | 1571.0                 | 260.96                 | 13,480                  | 1490                    |
| 0.70                 | 1771.11                | 200.11                 | 15,670                  | 2190                    |
| 0.80                 | 1965.14                | 194.03                 | 18,800                  | 3130                    |
| 0.90                 | 2117.73                | 152.59                 | 18,810                  | 10                      |
| 1.0                  | 2101.27                | – 16.46                | 19,630                  | 820                     |

- $T = 3.116M + 61.77$ (6)

The relationship between the maximum flash temperature and friction coefficient

The influence of friction coefficient on temperature. The tangential friction coefficient of the collision between the sample and the test plate is not easy to measure, while the accuracy of the friction coefficient directly affects the accuracy of the simulation of temperature field. First, discuss the influence of the change of friction coefficient on the maximum flash temperature of sample. The coefficient of friction between metals is well known 0.1–1, while the friction coefficient between TC4 and Q235 measured by rotational friction at the condition of different loads and relative speeds is between 0.1 and 0.2. So the influence of the change of friction coefficient on the flash temperature is discussed specially. The friction coefficient between 0.1 and 1.0 is roughly studied, and between 0.1 and 0.2 is emphatically studied. The mass of the heavy hammer is 60 kg, the friction coefficient is 0.1–0.2. Table 6 shows the
10) is also continuously increased first. When the friction coefficient is 0.8, the increase in stress becomes slow. The change trend of the stress and the maximum flash temperature is basically the same.

Use regression analysis to fit the temperature curve with the friction coefficient. By comparing the straight line, the quadratic curve and the cubic curve (Figure 11, Table 8), it is found that the fitting degree of the cubic curve is higher, and the fitting equation (9) is obtained.

\[
T = -2560\mu^3 + 2966\mu^2 + 1649\mu + 62.64
\]

**Verification of simulation results**

The hot surfaces generated by the collision are ultimately due to the friction and wear of the rough surfaces. The relative motion of the two objects produces friction. The contact surface is smooth and flat from a macroscopic point of view, but from a microscopic point of view, the friction surface is composed of countless irregular convex bodies. According to molecular friction theory, the contact between friction pairs is uneven. According to the researches, the protrusion height of the finely processed metal material surface is 0.05–0.1 μm, while the rough-processed metal material surface protrusion height is about 200 μm. The contact between the friction pairs, the actual contact surface is convex part of the contact, that is, the friction contact actually only occurs on a number of discrete rough peaks, then the collision contact can be regarded as the elastoplastic contact of a number of micro convex bodies.

Impact is different from friction, the contact time is extremely short, which will cause the contact point to overheat, that is, the flash temperature. The normal collision process between the sphere and the plane can be analyzed according to the Hertz contact theory. In order to facilitate the calculation, assuming that there are no other external forces except contact stress (deformation) and adhesion, and the influence of damping is negligible, thus, the contact motion in the normal direction could be described by

\[
m\ddot{\delta} = -P(\delta)
\]

\[
\delta(0) = 0, \dot{\delta}(0) = V_z
\]

Where \(m\) is the mass of the weight and the sample, \(P(\delta)\) is the function of the contact stress with respect to the depth of penetration, \(\delta\) is the depth of penetration, and \(V_z\) is the normal velocity of the collision.

According to the theory of elasticity.
\[
\delta = \left( \frac{9P^2}{16E^*R} \right)^{1/3} \tag{11}
\]

Where \( \delta \) is elastic deformation, \( P \) is the nominal contact pressure, \( E^* \) is the composite elastic modulus of the two materials, and \( R \) is the radius of the arc.

From equations (10) and (11), we can get:

\[
m\delta = -\frac{4}{3} E^* \sqrt{R^*} \delta^{3/2} \tag{12}
\]

Yuet et al.\(^{15}\) compared the deformation value predicted by the Hertz model with the deformation value of normal collision and inclined surface collision obtained by finite element simulation, and verified that the Hertz collision theory is applicable to the impact model beyond the range of elastic deformation and early plastic deformation.

When the contact materials are within elastic deformation range or early plastic deformation, the maximum contact pressure \( p_0 \) and the mean contact pressure \( p_m \) given by the Hertz solution are respectively:

\[
p_0 = \frac{3P}{2\pi \alpha^2} \tag{13}
\]

\[
p_m = \frac{P}{\pi \alpha^2} \tag{14}
\]

Where \( \alpha \) is the radius of the contact area.

Integrating equation (12) with respect to \( \delta \) leads to

\[
12 \left( \frac{d\delta}{dt} \right)^2 \bigg|_0 = \frac{1}{2} \left[ (d\delta/dt)^2 \right] = \frac{8 \sqrt{RE^*}}{15} \delta^{5/2} \tag{15}
\]

At the maximum penetration, \( \delta_{\text{max}} \), \( d\delta/dt = 0 \), which leads to

\[
\delta_{\text{max}} = \left( \frac{15mV_{\text{cm}}^2}{16 \sqrt{RE^*}} \right)^{2/5} \tag{16}
\]

The maximum value of the mean contact pressure during the elastic collision is:

\[
p_{\text{mm},\text{max}} = \frac{3}{2\pi} \left( \frac{4E^{*1/4}}{3R^{1/5}} \right) \left( \frac{5}{4} mV_{\text{cm}}^2 \right)^{1/5} \tag{17}
\]

Yuet al. used the approximate solution of the impact flash point temperature predicted by Tian and Kenedy, and assumed that the maximum contact area of the oblique impact is equal to the sliding contact area, then the maximum temperature rise (flash temperature) of the oblique impact is consistent with the temperature rise caused by the sliding contact. This hypothesis can be verified by finite element simulation of thermomechanical tilting impact. The maximum flash temperature rise of impact can be expressed as\(^{15,18-20}\):

\[
T_{\text{max}} = \frac{1.31 \alpha_{\text{max}} \mu \Delta m \max V_s}{K_s \sqrt{1.2344 + P_e, + k_p \sqrt{1.2344 + P_e}} \text{m}} \tag{18}
\]

Where \( \alpha_{\text{max}} \) is the maximum radius of the contact area, \( K_s \) and \( k_p \) are the thermal conductivity of the sample and the test board respectively, \( Pe \) is the Peclet number, defined as:

\[
Pe = \frac{V_s \alpha}{2K} \tag{19}
\]

Where \( V_s \) is the lateral velocity at which the heat source moves, and \( K \) is the thermal diffusivity, defined as:

\[
K = \frac{k}{\rho c} \tag{20}
\]

If the material undergoes plastic deformation during impact, that is, when the maximum contact stress exceeds the yield strength of the material, a plastic deformation zone will occur at the contact with lower strength.\(^{13}\) Assuming that the material meets the von Mises yield criterion, according to the Hertz contact theory, there is\(^{11}\):

\[
\begin{align*}
p_{\text{c}} = C_v Y \\
C_v = 1.234 + 1.256v \tag{21}
\end{align*}
\]

Where \( Y \) and \( \nu \) are the yield strength and Poisson’s ratio of the material, respectively. The yield strength of the TC4 titanium alloy is 825 MPa and the Poisson’s ratio is 0.34. Then it can be calculated that when the contact compressive stress is 1370.358 MPa, the titanium alloy sample begins to undergo plastic deformation.

When materials undergo plastic deformation, most of them will be plastic strengthened or softened which generally is linear strengthening or softening, then the
The calculated value (°C) | 86.1 | 117.4 | 148.1 | 189.8 | 211.7 | 248.3
Relative errors (%) | 9.1 | 4.9 | 2.1 | 2.3 | 0.7 | 0.5

The mass of hammer (°C) | 10 | 20 | 30 | 40 | 50 | 60
The simulated value (°C) | 93.9 | 123.2 | 151.2 | 194.1 | 213.1 | 249.5
The calculated value (°C) | 86.1 | 117.4 | 148.1 | 189.8 | 211.7 | 248.3
Relative errors (%) | 9.1 | 4.9 | 2.1 | 2.3 | 0.7 | 0.5

The relationship between compressive stress and deformation is:

\[
\begin{align*}
\sigma_c &= \sigma_y + k(\sqrt{\delta} - \sqrt{\delta_y}) \\
\sigma_y &= \frac{2E\sqrt{\delta_y}}{\pi\sqrt{R}}
\end{align*}
\] (22)

Then the maximum deformation of impact can be obtained according to the law of conservation of energy as:

\[
\frac{1}{2}mv_z^2 = \int_0^{\delta_y} P_x d\delta + \int_{\delta_y}^{\delta_{max}} P_y d\delta
\] (23)

Equation (23) leads to:

\[
(p_y - k\sqrt{\delta_y})\frac{\pi R(\delta_{max} - \delta_y)^2}{2} + \frac{8}{15}k\pi R \left[\delta_{max}^\frac{3}{2} - 2\left(\frac{\delta_{max} + \delta_y}{2}\right)^\frac{3}{2} + \delta_y^\frac{3}{2}\right] + P_y(\delta_{max} - \delta_y)
\] (24)

\[
= \frac{1}{2}mv_z^2
\]

On the one hand, the temperature rise of the impact comes from the heat conversion of sliding friction, on the other hand the heat generated by the plastic deformation of the material. Then the maximum flash temperature rise caused by tangential friction is:

\[
T_{f,max} = 1.31\alpha_{max}^\mu V_k[p_y + k(\delta_{max} - \delta_y)]
\] (25)

Another part of the temperature rise of the impact comes from the plastic deformation heat of the material. The mutual sliding between the atomic planes will generate microscopic frictional heat. The gradual accumulation of atomic frictional heat can produce an unignorable temperature rise. Plastic deformation heat, which is the heat converted by plastic strain energy, accompanied by the heat conduction, heat radiation and latent heat of the material. Since the impact time is very short, it can be approximated as adiabatic treatment, that is, the heat radiation and latent heat are ignored, and the plastic strain energy is completely transformed into the impact surface. The temperature rise, The solving equation of the temperature rise is:

\[
J\rho c\bar{T} = \sigma(\varepsilon^p)\varepsilon^p
\] (26)

Where \(J\) is the mechanical thermal equivalent, \(\rho\) and \(c\) are the material density and specific heat, respectively, \(\sigma\) is the stress, and \(\varepsilon^p\) is the plastic strain.

Integrating equation (26) leads to:

\[
T_p = \frac{(p_y - k\sqrt{\delta_y})\delta_{max}^\frac{3}{2} + \frac{3}{2}k\delta_{max}^{3/2}}{J\rho c}
\] (27)

Then when the impact causes the material to appear inconsistent and neglected plastic deformation, the maximum flash temperature rise of the collision is the sum of the temperature rise caused by friction and the temperature rise caused by the plastic deformation of the material, is:

\[
T_{max} = T_{f,max} + T_p
\] (28)

If the material is assumed to be an ideal elastoplastic material, that is, the plastic strengthening or softening of the material can be ignored \((k = 0)\), then after the material yields, the contact compressive stress \(p_A\) in the plastic deformation zone will always remain unchanged.

It can be seen from the impact stress results obtained from the simulation that the impact contact is far beyond the elastic deformation range of the material, and a non-negligible plastic deformation occurs. In order to use the theoretical calculation results to verify the accuracy of the simulated maximum flash temperature more clearly, the maximum flash temperature under the fully elastic collision condition and it under the assumption that the material is an ideal elastic-plastic material are calculated according to the Hertz contact theory, and the it under the assumption of elastic-plastic linear strengthening.

Under the action of weights of different masses, the maximum flash temperature of complete elastic collision can be calculated according to formulas (10)–(19), and the flash temperature value obtained under the same conditions is the highest (Figure 12). The impact flash temperature under the premise of ideal elastic-plastic material is calculated according to formulas (24), (26), and (27) (i.e. \(k = 0\)). From the calculation results, it can be found that the flash temperature is little affected by the mass of the hammer. For every 10kg
increase in the mass of the hammer, the maximum flash temperature value increases by about 1°C, and the maximum flash temperature value is the lowest under the same conditions. The calculation under the assumption of elastic-plastic linear strengthening is based on formulas (23) and (25)–(27), it can be clearly seen from the simulation results that the material will undergo plastic strengthening, and the calculated result obtained by taking $k = 10^{10}$ is between complete elastic contact and ideal elastic-plastic. The hypothesized solutions are very close to the simulation results. Compared the calculated values and the simulated values, the relative errors are the ratio of the difference between the simulated value and the calculated value to the calculated value. The comparison results are shown in Table 9. The relative errors are not too large, so the simulated and calculated value agreed well. It can prove the accuracy of simulated results.

Analysis of factors affecting the maximum flash temperature

According equation (24), the factors affecting the maximum flash temperature are contact compressive stress, relative velocity, coefficient of friction between acting surfaces, ambient temperature and the nature of materials. For the falling gravity hammer test, the relative velocity and nature of sample and text board is fixed, thus only need to consider the influence of contact pressure stress and friction coefficient on temperature. The simulation obtains the highest flash temperature values under the mass of each heavy hammer with different friction coefficients in Table 10.

It can be seen intuitively from Figure 13 that the friction coefficient is constant, and the highest flash temperature increases with the mass of the weight. When the mass of the weight is constant, the highest flash
In short, the control of the coefficient of friction of impact friction pairs is one of the important methods to control the temperature of the hot surface.

**Table 11.** Contrast between simulated and calculated values of flash temperature.

| Friction coefficient | Momentum of the sample (kg m/s) | Simulated temperature (°C) | Calculated temperature (°C) | Relative errors (%) |
|----------------------|----------------------------------|-----------------------------|-----------------------------|---------------------|
| 0.10                 | 62.6                             | 94                          | 108                         | 12.9                |
| 0.12                 | 125.2                            | 153                         | 148                         | 3.4                 |
| 0.14                 | 187.8                            | 201                         | 205                         | 2.0                 |
| 0.16                 | 250.4                            | 283                         | 281                         | 0.7                 |
| 0.18                 | 313.0                            | 369                         | 374                         | 1.3                 |
| 0.20                 | 375.6                            | 495                         | 485                         | 2.1                 |

The highest flash temperature under different weights and friction coefficients can be obtained by equation (29).

$$T = 132.4 - 0.2515\rho - 806.5\mu + 6.879\mu\rho + 3251\mu^2 - 1.301p\mu^2 - 2396\mu^3$$

(29)

The highest flash temperature under different momentums of the sample and different friction coefficients. The fitted surface is shown in Figure 14 and the fitted equation is equation (29).

The highest flash temperature of different momentums of the sample and different friction coefficients, the fitted surface is shown in Figure 14 and the fitted equation is equation (29).

Compared the calculated values and simulated values of the flash temperature at different conditions. The relative errors are the difference between the simulated value and the calculated value to the calculated value. The comparison results are shown in Table 11. The relative errors are not too large, so the simulated and calculated value agreed well. It can prove the accuracy of formula (29).

Assuming that the weight of the equipment made of TC4 titanium alloy exceeds 27.5 kg, then the mass of hammer can be determined to be 60 kg. If the potential ignition source of impact friction spark is not considered, only the highest flash temperature is controlled below the minimum ignition temperature of methane-air mixture 650°C, according to equation (29), the critical friction coefficient can be calculated as 0.25. Therefore, the method to control the hot surface generated by impact as an effective ignition source can be to reduce the friction coefficient between the friction pairs, such as improving the material processing accuracy, reducing the surface roughness and thus reducing the friction coefficient. In addition, the roughness of the material also has an effect on the contact thermal resistance. Generally, the greater the surface roughness, the greater the contact thermal resistance. The increase in contact thermal resistance will make it more difficult to dissipate heat from frictional high-temperature hot-spots, resulting in higher temperatures and higher risk of use. In short, the control of the coefficient of friction of impact friction pairs is one of the important methods to control the temperature of the hot surface.

**Conclusion**

In this paper, Abaqus finite element analysis software was used to simulate the temperature field generated during impact of TC4 titanium alloy and Q235A test plate, and combined with elastic-plastic collision theory and heat transfer theory, the maximum flash point temperature of TC4 titanium alloy sample was deeply studied, and the conclusions are as follows: (1) The impact model of the falling gravity hammer test was analyzed, and the mathematical models of volume temperature and maximum flash point temperature were deduced, and the influencing factors of impact volume temperature and maximum flash point temperature under different conditions were obtained. (2) The influence of mass on impact temperature field is analyzed by simulation and theory, and the argument that hot surface temperature is only related to velocity and has nothing to do with mass is denied. Whether the flash temperature is related to the mass needs to consider the elastic-plastic deformation of the material itself and the strengthening or softening of the plastic shape. Only when the compressive stress reaches the extreme value or the material is ideal elastic-plastic material, the flash temperature is independent of the mass. In addition to the properties of materials, the main factors affecting compressive stress are friction coefficient, relative velocity and normal load (which is the mass of heavy hammer in this paper). (3) Elastic-plastic collision theory is used to calculate the flash temperature, the largest simulation value with the material shape reinforce assumptions coincided basically with the calculated results, the accuracy of the simulation is verified by the calculation results on the one hand, on the other hand shows that the impact plastic material before and after reinforcement, and the plastic hardening approximate to linear strengthening (reinforcement index $k$ of about $10^{10}$). (4) In the falling gravity hammer test, the relative speed of impact is constant and the weight is 10–60 kg. If the surface friction coefficient is constant, the maximum flash temperature increases with the increase of
the weight. (5) The measurement accuracy of friction coefficient directly affects the measurement accuracy of the maximum flash temperature of collision. The friction coefficient deviation is 0.01, and the flash temperature will float 20°C–30°C. Under other impact conditions, the friction coefficient varies from 0.1 to 1.0, and the flash temperature increases at first, then slowly, and finally slightly decreases. (6) In the falling gravity hammer test, the factors influencing maximum flash temperature are momentum and friction coefficient. Using regression analysis to study the variation law of flash temperature with momentum and friction coefficient, a mathematical model that can predict the value of flash temperature is obtained, with the impact conditions are that the impact momentum is between 62.6 and 375.6 kg·m/s, the surface friction coefficient is between 0.1 and 1.0. Therefore, to prevent hot surfaces be an effective ignition source, the method is to set a critical friction coefficient or critical momentum in impact.

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