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Research on the Impact Behavior of Molten Metal on the Mold Shell in Gravity Casting of Large Titanium alloy Castings

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Abstract

The impact behavior of molten metal on the mold shell in gravity casting of large titanium alloy castings by investment precision castings was studied. The physical and mechanical models of the impact of molten metal on the mold shell during the pouring process were constructed using numerical simulation. The effects of molten metal pouring rate and pouring weight on the maximum impact force of the mold shell were studied. The research results indicated that during the entire pouring process, the impact force of the first molten metal contacting the mold shell was higher than subsequent molten metal. The maximum impact force increased with the increase of pouring rate and pouring weight. The total impact force of the molten metal on the mold shell was composed of the instantaneous impact force converted from instantaneous impulse and itself gravity. The instantaneous impact force of the molten metal that first impacts the mold shell was much greater than its own gravity, while the impact force of the molten metal at the end of pouring was much less than its own gravity. The maximum impact force on the mold shell of a large casting with a pouring weight of 800kg was about three times higher than that of a medium-sized casting with a pouring weight of 80kg.The difference in the total impact force on the mold shell between them mainly comes from the instantaneous impact force converted from instantaneous impulse.

Key words: *impact force; mold shell; pouring rate; pouring weight; instantaneous impulse*

1 Instruction

Investment casting has various advantages such as near net forming, good surface quality, high dimensional accuracy, environmental friendly performance, and is suitable for mass production of complex castings [1-3]. It is the preferred process for manufacturing high-quality structural components for aerospace applications. The investment casting process is applicable to almost all metal materials, such as aluminum alloy [4], magnesium alloy [5], titanium alloy [6-7], super alloy [8-9], cast steel, etc. Mold shell preparation is a necessary process in investment casting. The quality of the mold shell has great influence on the metallurgical quality and surface roughness of the casting [10-11]. Therefore, a large amount of researches have been conducted on how to improve the surface fire resistance [12-14], collapsibility and strength [15-16]. The preparation process system and quality evaluation system of mold shell for investment casting have been formed [17-19].

As aerospace equipment technology develops, the casting structural dimension is becoming larger while the pouring weight is also increasing. Taking titanium alloy casting as an example, the pouring weight of molten metal for small and medium-sized structural casting is 80~150kg using a vacuum arc consuming shell furnace. The pouring time is about 6-10 seconds, and the pouring weight per second is 10～15kg/s. For large casting with the casting weight over 300kg, the pouring weight will reach 800~1000kg with the addition of the pouring system. Considering that the solidification range of titanium alloy is relatively narrow, it is necessary to complete the pouring in a relatively short time in order to ensure the complete filling of thin-walled parts. The pouring time is usually about 15 seconds, and the

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pouring weight per second reaches about 60kg/s. Obviously, the large pouring weight of large casting has a great impact on the mold shell, which requires the mold shell to have relatively high anti-impact strength. The mold shell will crack for large casting if its strength is not enough. However, there is currently a lack of research reports on the relationship between pouring weight, pouring rate, and mold shell strength. So it is much difficult to predict the mold shell strength based on pouring weight.

For large casting, the cost of a single pour test is high. This paper took gravity cast titanium alloy casting as the research object, established a physical model of molten metal impact on the mold shell, and studied the impact behavior of molten metal on the mold shell through finite element numerical simulation, as well as the effects of pouring rate and pouring weight on the maximum impact force on the mold shell. This work will help for understanding the impact behavior of molten metal on the mold shell during pouring, and provide reference for predicting mold shell strength of pouring large casting.

2 Test Materials and Methods

2.1 Physical Model of molten metal Impact on the Mold Shell

Titanium alloy castings are usually poured by gravity pouring using a vacuum arc consumable shell furnace. Figure 1 (a) shows the pouring schematic diagram of titanium alloy castings. Considering that the diameter of the crucible is usually larger than the diameter of the main ingate of the mold shell, in order to avoid the dispersion of molten metal, a funnel has been added between the crucible and the mold shell. The funnel plays a role in collecting the molten metal, and the guide tube ultimately gathers the molten metal into a complete liquid flow and guides the liquid flow into the mold shell.

Considering that the molten metal poured from the crucible is obstructed and collected by the funnel, the velocity of molten metal flowing out from the guide tube is significantly reduced. To simplify the model, it is assumed that the initial velocity of the molten metal when left out from the guide tube is 0, and then it impacts the mold shell in a free falling manner. Additionally, considering the complex structure of the gating system and casting, the bottom mold shell of the gating system is simplified as a large planar structure. Based on the above assumption, a simplified model of molten metal impact on the mold shell of titanium alloy casting was obtained, as shown in Figure 1 (b).

In the actual pouring process of titanium alloy casting, the main process parameters that affect the impact behavior of molten metal on the mold shell included molten metal density, pouring temperature, mold shell preheating temperature, pouring rate, and pouring height. Ti-6Al-4V alloy was used in this work. A medium-size casting with a pouring weight of 80kg and a large casting with a pouring weight of 800kg were applied to conduct research. The main thermal-physical and process parameters were shown in Table 1 and Table 2, respectively.

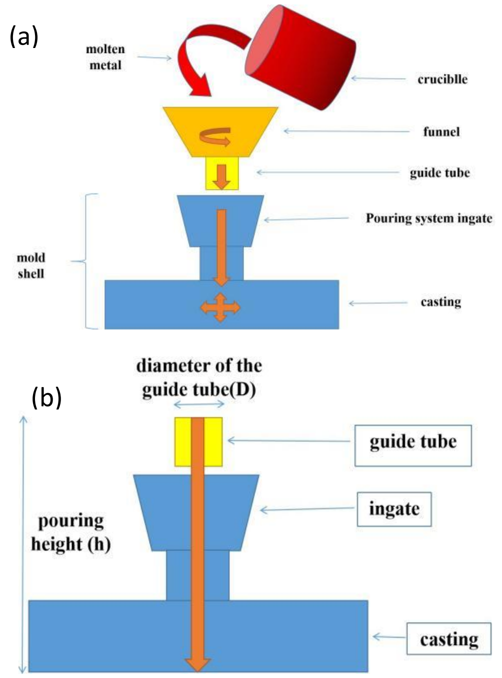

Figure 1 Actual schematic diagram (a) and simplified model (b) of titanium alloy casting in a vacuum arc consuming shell furnace

Table 1 the main thermal-physical parameter

Alloy (wt %)	Melt liquid density *P* (g/cm^3)	Melt liquid Temperature *T* (℃)	Mold shell preheating temperature *T2* (℃)
Ti-6Al-4V	4.5	1750	400

Table 2 the main process parameter

Alloy (wt %)	Pouring weight $\triangle m$ (kg)	Pouring height *H* (mm)	The diameter of the guide tube *D* (mm)	Pouring time *t* (s)	Pouring rate *V* (kg/s)
Medium casting	80	600	60	6	13
Large casting	800	1250	120	13	65
				15	57
				18	47

2.2 Mathematical Model of Melt Impact on the mold shell

A mathematical model for the filling process of the melt was constructed based on the process of the melt impacting the mold shell. Temperature field was calculated as follow.

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \frac{\partial T}{\partial x} + \rho c_p v \frac{\partial T}{\partial y} + \rho c_p w \frac{\partial T}{\partial z} =$$
$$\frac{\partial}{\partial x}\left(k_i \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_i \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_i \frac{\partial T}{\partial z}\right) + \rho L \frac{\partial f_S}{\partial t} \quad (1)$$

In the formula-1, T is the molten metal temperature, ρ is the density of the molten metal, c_p is the specific heat of the metal, k is the thermal conductivity of the metal, L is the latent heat of solidification phase transformation, f_s is the solid fraction of the unit, t is time, u, v, w are the three components of the velocity vector.

Continuity equation of flow field as follow:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (2)$$

X-direction momentum equation

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \rho w \frac{\partial u}{\partial z} =$$
$$\frac{\partial}{\partial x}\left(\mu_i \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_i \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_i \frac{\partial u}{\partial z}\right) - \frac{\partial p}{\partial x} + S_x \quad (3)$$

In the equation, μ is the viscosity, p is the fluid pressure, and Sx is the source term of the momentum equation of the X equation.

Y-direction momentum equation

$$\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \rho w \frac{\partial v}{\partial z} =$$
$$\frac{\partial}{\partial x}\left(\mu_i \frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_i \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_i \frac{\partial v}{\partial z}\right) - \frac{\partial p}{\partial y} + S_y \quad (4)$$

Sy is the source term of the momentum equation of the Y equation.

Z-direction momentum equation

$$\rho \frac{\partial w}{\partial t} + \rho u \frac{\partial w}{\partial x} + \rho v \frac{\partial w}{\partial y} + \rho w \frac{\partial w}{\partial z} =$$
$$\frac{\partial}{\partial x}\left(\mu_i \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_i \frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_i \frac{\partial w}{\partial z}\right) - \frac{\partial p}{\partial z} + S_z \quad (5)$$

Sz is the source term of the momentum equation of the Z equation.

A mathematical model of the impact force on the mold wall was constructed based on the principle of full differential gradient of reverse normal velocity, and the schematic diagram of the impact force was shown in Figure 2.

$$\mathrm{N} = -\rho(\Delta v_{nx} * v_x + \Delta v_{ny} * v_y + \Delta v_{nz} * v_z) / s \quad (6)$$

N is the impact force at the contact point, Δv_{nx}, Δv_{nx} are the normal velocity difference, v_x v_y v_z are the velocity components in the difference direction, ρ is the fluid density, and s is the contact area.

According to the formula, the impact force of molten metal on the mold shell is directly related to the speed vector. Therefore, this paper combined the actual model and mathematical model, and used Huazhu CAE software to conduct finite element simulation calculation of the impact behavior of molten metal on the mold shell.

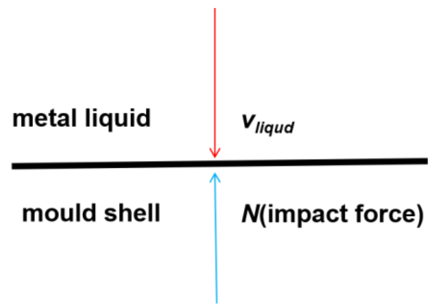

Figure 2 Schematic diagram of molten metal contacting wall impact force

3 Testing Results and Analysis

impact behavior of molten metal on the mold shell

Figure 3 showed the evolution behavior of the melt velocity vector field during the melt filling process with a pouring time of 13 seconds and a pouring rate of 65kg/s. It could be seen that the first molten metal flowing out from the guide tube impacted the center of the mold shell aligned with the guide tube, and the velocity vector at the center of the mold shell was the highest. When the molten metal first contacts the mold shell (0.66s), the instantaneous velocity at the center of the mold shell reached an appropriate amount of 421m/s, as shown in Figure 3 (b). As the pouring process progresses, the molten metal gradually filled the mold shell from the center to the far end. From the simulation results, the velocity vector field in the center of the mold shell was significantly greater than that in other parts. Even if the molten metal completely flowed to the far end of the mold shell, the appropriate velocity in the center area was still the maximum, as shown in Figure 3 (c) and Figure 3 (d). From Figure 3 (d), it could also be seen that during the filling process of the molten metal from the center to the far end of the mold shell, the velocity vector of the melt gradually decreased, and the velocity at the farthest end was moderately minimum. As the molten metal filling gradually progresses, the melt velocity in the central region gradually decreased. When the molten metal completely filled the bottom runner, the velocity in the central region decreased to an appropriate level of 200m/s, as shown in Figures 3 (e) and 3 (f).

Additionally, impact behaviors of molten metal on the mold shell at the pouring rates of 47kg/s and 57kg/s were simulated and analyzed. According to the simulation results, it could be seen that the impact behaviors of the molten metal on the mold shell under two pouring rate conditions are nearly similar to that at the pouring rate of 65kg/s. In summary, the velocity vector in the center area of the mold shell was the largest when the molten metal first contacted the mold shell. Although the velocity gradually decreased as the pouring process progressed, the velocity in the center area was always higher than those of other areas.

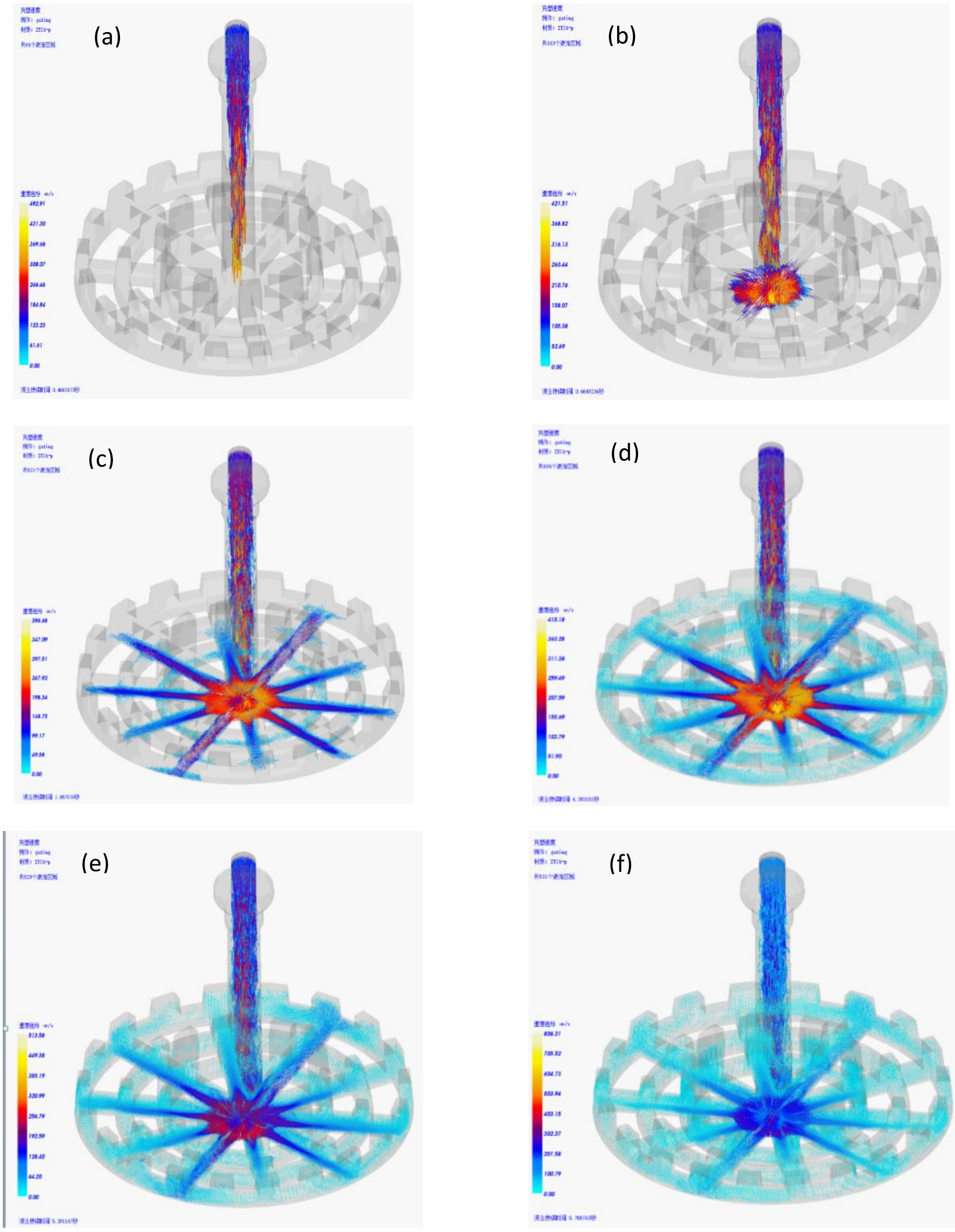

Figure 3 The melt velocity vector field as the filling time with a pouring time of 13 seconds and a pouring rate of 65kg/s.(a)0.466s,(b)0.664s,(c)1.654s,(d)4.36s, (e) 5.36s, (f)5.76s

3.2 Effect of pouring rate on impact behavior

Based on the above analysis, it was concluded that the velocity vector in the center area of the mold shell was the highest. According to the formula-6, the force exerted by the molten metal on the mold shell was positively correlated with the velocity vector. In order to further analyze the relationship between pouring rate and mold shell force, this paper studied the evolution behavior of molten metal impact on the center of the mold shell at pouring times of 13 seconds, 15 seconds, and 18 seconds for large casting. Figure 4 showed the variation curve of the force exerted by the molten metal on the mold shell over time under three different pouring rates. The force exerted by the molten metal on the mold shell occurred in the initial stage of the molten metal impacting the mold shell, and as the pouring process progressed, the force gradually decreased. At the same time, the maximum force varied in a saw tooth shape, indicating that the impact force of the molten metal on the mold shell was not continuous. It inferred that the molten metal flow from the guide tube was not continuous. So it was suggested that the effect of the first molten metal should be mainly focused when evaluating the force of molten metal on the mold shell.

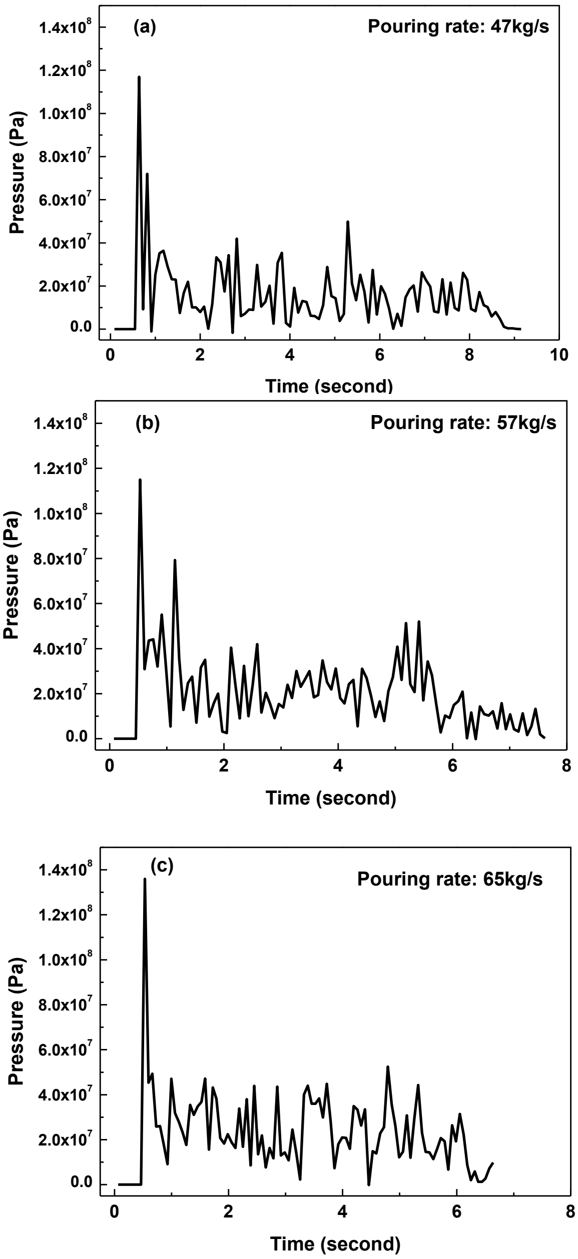

Figure 4 The curves of the force of molten metal on mold shell under different pouring rates

(a)47kg/s, (b)57kg/s，(c)65kg/s

Table 3 Showed the contact time of the first molten metal with the mold shell and the maximum force under different pouring times and pouring rates. The maximum force exerted by the first molten metal on the mold shell was about 115MPa when the pouring rate is 47g/s. As the pouring rate increased to 57kg/s and 65kg/s, the maximum force exerted by the first molten metal on the mold shell increased to 118MPa and 136MPa, respectively. It could be seen that as the pouring rate increased, the force of the molten metal on the mold shell gradually increased.

Table 3 Relationships among pouring time, pouring rate and maximum impact force

Pouring time (s)	Pouring rate (kg/s)	Time for the maximum forc e(s)	The maximum force (MPa)
13	65	0.532	136
15	57	0.534	117
18	47	0.547	115

As the pouring time increased from 13 seconds to 18 seconds, the average pouring rate decreased from 65kg/s to 47kg/s. However, the times between the first molten metal flowing out from the guide tube and contacting the mold shell were near, increasing from 0.532 seconds to 0.547 seconds. It was assumed in this paper that the melt flowed out from the guide tube in a free falling manner and impacted the mold shell. Because the pouring height from the guide tube to the mold shell was same, the time for the first molten metal flowing out from the guide tube and contacting the mold shell was also same.

3.3 Effect of pouring weight on melt impact behavior

Compared with large castings, the pouring time and pouring rate together with pouring height for medium-sized castings have been reduced. Up to date, It has been not yet known whether the impact behavior of metal liquid on the mold shell obtained from large castings was applicable to medium-sized castings. Therefore, this paper further studied the effect of molten metal on the mold shell of medium-sized castings with a pouring weight of only 1/10 of large casting through numerical simulation. The main process parameters was showed in Table 2. Figure 5 was the picture of the impact velocity vector of the molten metal on the mold shell during the casting time of 0.20s.

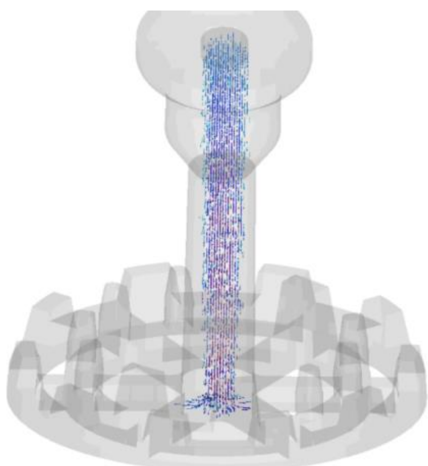

Figure 5 Velocity vector field of molten metal impact force on the mold at the pouring time of 0.20s for medium size casting

The impact force of molten metal on the mold shell varied between medium-size and large castings. Figure 6 showed the variation of the impact force of the molten metal on the mold shell of the two castings during the pouring process. From the figure, it could be seen that the instantaneous maximum impact force of the molten metal on the mold shell was 35MPa for medium-sized castings with the pouring weight of 80kg, while the maximum impact force for large casting with the pouring weight of 800kg was 117MPa. The impact force on the mold shell for large casting was about three times that of medium-sized castings.

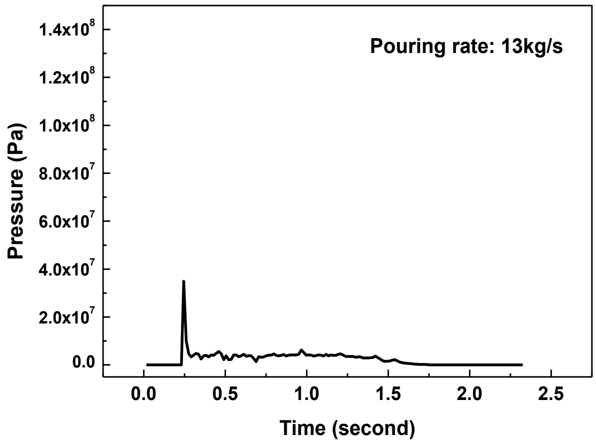

Figure 6 The curve of the force and pouring time for medium sized castings

3 Discussion

During gravity casting process, the molten melt flowed from the guide tube to the mold shell in a free falling manner. In fact, the impact behavior of molten melt on the mold shell could be attributed as a liquid-solid impact [20-22]. Based on the above analysis, this paper constructed a physical model of the impact of molten metal on the mold shell. The total impact force of molten metal on the mold shell included instantaneous impact force and itself gravity. The instantaneous impact force was the conversion of the impact impulse from momentum of freely falling metal molten. And itself gravity was the weight of the molten metal. The specific calculation formula of the impact force was as follows:

$$\mathrm{I} = \mathrm{F}dt = \Delta mv \tag{7}$$

$$\mathrm{F} = \Delta \mathrm{mv/dt} \tag{8}$$

$$\mathrm{F} = \Delta \mathrm{mv}/dt = \Delta \mathrm{m}\sqrt{2\mathrm{gh}}\,/\,dt \tag{9}$$

I is the instantaneous impulse of the molten metal impacting the mold shell, *F* is the instantaneous impact force, *dt* is the instantaneous impact time, $\triangle m$ is the melt mass, *v* is the velocity vector when the melt just contacts the mold shell, g is the gravitational acceleration, and *h* is the pouring height. In this paper, *h* is the distance of the melt from the guide tube to the mold shell.

According to Formula-8, assuming the instantaneous impact time remained constant, the instantaneous impact force of the molten metal on the mold shell was proportional to the velocity vector when the melt just contacted the bottom of the mold shell. By simulation and calculation of the velocity vector, the instantaneous impact force of the melt on the mold shell could be calculated. According to Formula -9, the instantaneous impact force of the molten metal on the mold shell was positively proportional to the pouring weight and pouring height. In addition to the impact force converted from momentum, the gravity of the melt itself also exerted pressure on the mold shell. Based on the above analysis, the total impact force on the mold shell N=F (the impact force converted from momentum)+G (itself gravity) was calculated comprehensively.

$$\mathrm{N} = \mathrm{F} + \mathrm{G} = \Delta m\sqrt{2gh}\,/\,dt + \Delta mg \tag{10}$$

Considering that the mold shell was made of ceramic material, when the first molten metal impacted the mold shell, it was assumed that the mold shell was a quasi-rigid object with almost no deformation at the moment of impact. The contact time between the molten metal and the mold shell was relatively short, resulting in a maximum impact force converted from impact impulse. When the second molten metal impacted the mold shell, there was already a portion of the molten metal at the bottom of the mold shell. As the molten metal was a viscous plastic fluid, it had a buffering effect, thus reducing the impact force converted by the impact impulse. When the molten metal filled the bottom runner of the mold shell, the molten metal on the surface of the mold shell had important buffering effect (the thickness of molten metal was about 100mm). It was approximately inferred that the impact force converted by the impact impulse was almost zero. Therefore, when the molten metal first impacted the mold shell, the impact force converted by he impact impulse was much greater than itself gravity. When the first wave impacted the mold shell, the total impact force mainly depended on the impact force F; When the melt filled the bottom of the mold shell, the impact force converted by the impact impulse was almost zero, and the total impact force mainly depended on itself gravity. Finally, a total impact force model of molten metal on the mold shell was constructed (Figure 7).

According to formula -10, it could be seen that the total impact force was positively correlated with the pouring height and pouring rate. The total impact force of medium-sized casting and large castings were calculated by formula -10. Due to the extremely short impact time of molten metal on the mold shell, the contact time was assumed as 0.001 seconds for medium and large castings. In addition, considering that the molten metal flows out of the guide tube in a free fall manner and falls in a raindrop like manner, the pouring height of medium-sized castings was relatively small. The area of the molten metal contacting the mold shell was approximately 3/4 of the diameter of the guide tube, and the pouring height of the large casting was relatively large. The area of the molten metal contacting the mold shell was approximately 1/2 of the diameter of the guide tube. According to the above data, the impact force of medium-sized castings was 22290N, and their own gravity was 127N; The impact force of the large casting was 321733N, and its own gravity was 737N. The total impact forces of both them were 22417N and 322370N, respectively, with corresponding total pressure of 31.73MPa and 114MPa. This was basically similar to the simulation results in this paper. The above calculation results could effectively explain the difference in different total impact force on the mold shell for medium and large castings.

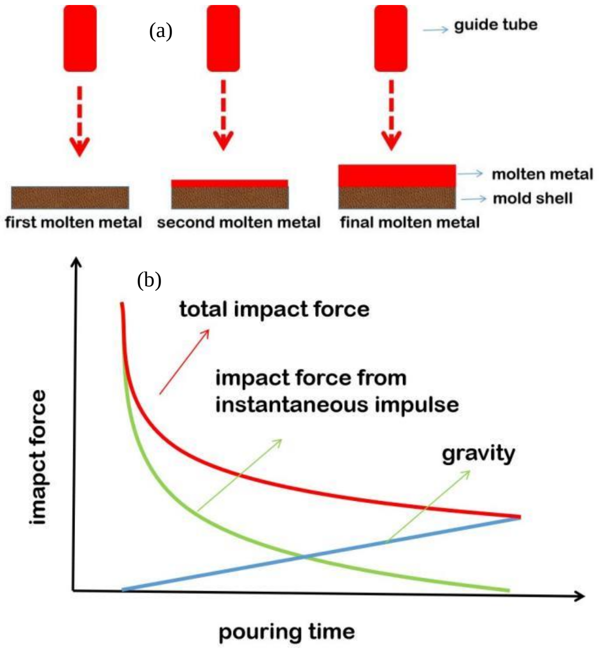

Figure 7 Physical and mechanical models of molten metal impact on mold shell

(a) physical model; (b)mechanical model

Therefore, the pouring weight of large castings was relatively large, and the impact force on the mold shell was much greater than that of medium castings, which put forward higher requirements for the strength of the mold shell. By adding carbon fibers, nylon, and other methods, the strength of the mold shell can be improved, but further work is needed to determine the detailed process parameters [23].

Table 4 The parameters for melt impact calculation of medium and large castings

Casting	Pouring weight △m (kg)	Pouring height H (m)	The diameter of the guide tube D (m)	Contact time dt(s)	The diamater of contact area (m)
medium	13	0.60	0.06	0.002	0.03
larger	65	1.25	0.12	0.001	0.06

Table 5 Total impact force of molten metal on the mold shell for medium and large castings

Casting	Impact force F (N)	Gravity G (N)	Total impact force N (N)	Total pressure (MPa)
Medium	22290.36	127.40	22417.76	31.73
Larger	321733.59	637.00	322370.59	114.07

4 Conclusion

When the molten metal first contacts the mold shell, the velocity vector in the center area of the mold shell is the highest. As the pouring process progresses, the velocity vector gradually decreases, but the velocity vector in the center area is always the highest.

The total force of the first molten metal on the mold shell increased with the increase of pouring rate and pouring weight. Compared to a medium-sized titanium alloy casting with a pouring weight of 80kg, a large casting with a pouring weight of 800kg had a maximum total impact force of 118MPa on the mold shell from the first molten metal, which was about three times higher than that of a medium-sized casting. It was attributed to the effects of pouring rate on the total impact force.

The total force of molten metal on the mold shell included the instantaneous impact force converted from instantaneous impulse and the gravity of the melt itself. When the molten metal first contacted the mold shell, the instantaneous impact force was much greater than itself gravity. The total impact force of the first molten metal was much greater than that exerted by the subsequent molten metal. At the end of the pouring process, the total impact force of molten metal on the mold shell was importantly reduced, of which the instantaneous impact force converted from instantaneous impulse was reduce to zero.

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Investigation and writing — original draft preparation, Zhu X.; simulation analysis, Zhu C.; Lin B.; Conceptualization, Wang Z.All authors have read and agreed to the published version of the manuscript.

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