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Materials

Basic rules for rheologic forging process of semisolid alloy

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Abstract: Semisolid mold forging is a major type of semisolid processing, which is different from neither traditional mold forging nor traditional permanent casting. However, processing defects are often seen in work pieces because of lacking available rules for the process design and control. Some basic rules for the process design and control, simply named the shortest flowing length, pressure filling and the minimum uplifting mold pressure, are advanced in the paper based on amount of researches and experiments. The equations to determine the major process parameters are given out such as the filling pressure, forming pressure and locking mold pressure for the process design and control. The rules and equations are experimentally proved available and applicable by several actual work pieces produced by the semisolid forging process.

Key words: semisolid alloy; rheologic forming; mold-forge; process design; rule

1 Introduction

Semisolid forging, a new process to make metals and alloys shaped, is a major type of semisolid forming process. Its obvious advantages are easier to produce complex work pieces because of its excellent forming ability, more flexible to shape, and more compact in the inner quality for its high pressure than the semisolid die casting process. Although there are many examples to successfully produce work pieces by the process in the world [1, 2], the process defects such as shrinkages, cracks, cold shut, shut run and so on are often seen in the products due to lacking valuable design rules [3, 4]. So it is necessary and urgent to build basic rules for the design and control of the semisolid rheologic forging process.

It is known that a semisolid process is generally divided into two essential types, one is called rheologic forming process, the other is named thixologic forming process. Similarly, the semisolid forging process can also be divided into two types: semisolid rheologic forging process and semisolid thixologic process. In the later process the billets used to form can keep a certain shape even at the semisolid temperature, therefore its process design and control is similar to the traditional forging process of solid materials. However, in the rheologic forge process, the charge used to form is semisolid slurry that can flow like common liquid without any special shapes. So the process design and control for the rheologic forging process is a special problem differing from either the solid forging process or the liquid casting process. If the process design and control is not reasonable, some defects will be seen in the products.

Although some suggestions for the process design and control can be seen in some papers [5, 6], the specific and complete rules are still necessary to explore in detail. Three basic rules for the semisolid forging process design and control and three basic equations used to determine the process parameters are experimentally and theoretically advanced in the paper according to previous researches and recent experimental results.

2 Three Basic rules

To determine the process project is a key task in the process design, especially in the selection of forming equipment and mold designs. The major contents of a process project include determining the forming situation of a wok piece, selecting the dividing mold planes, calculating the key process parameters such as the filling pressure, locking mold pressure and forming pressure, and deciding the number and shapes of the core used to form inner holes. Although a process project is strongly relative to the shape and demands of work pieces, there still exist some common principles to be abided. It is found by theoretically and experimentally researches that the common basic principles or rules are: (1) the shortest flowing length, *i.e.* the length to be filled must be shorter than the limit flowing length of the alloy; (2) pressure filling, which

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demands the most parts of the mold forcefully filled by a pressure, *i.e.* the mold is filled with pressure and avoiding filling without pressure as much as possible; (3) the minimum uplifting mold pressure, *i.e.* keep the pressure to uplift mold less than that to lock mold.

If the first rule is violated in the process design or control, the work piece cannot be completely formed at all. If the second one is breached, it is difficult to obtain a dense work piece. If the third one is violated, the process cannot carry out because of safety or economics. Only if the three basic principles or rules are abided well, a fine product may be produced out.

2.1 The shortest flowing length (SFL) rule

The essence of the semisolid rheologic forging is a process to make semisolid slurry flow into molds, be solidified into solid and compensate the shrinkage under the action of a pressure. However, semisolid slurry can flow only under some conditions. The condition is experimentally proved that the pressure or sheering stress acted on the slurry must be larger than the critical stress of the slurry [7, 8]. However, the critical stress is varied with the microstructure and temperature of the slurry, which may change during the flowing process even the outer pressure keeping constant. In fact the longer the length flowed of the slurry, the lager the loss of pressure and temperature along the length filled. As a result, the critical stress of the slurry increases with the flowing length because of the decrease of its temperature during the flowing process [5, 7]. When the flowing length is larger than some value, named limit flowing length, the slurry becomes a solid and can not flow at all. Only if the length to be filled is shorter than the limit length, a perfect work piece can be obtained. So the first basic principle to be abided in the rheologic forging process project design is that the maximum length to fill is shorter than the limit flowing length of the slurry, simply named the shortest flowing length rule (SFL rule for short), as shown in **figure 1**.

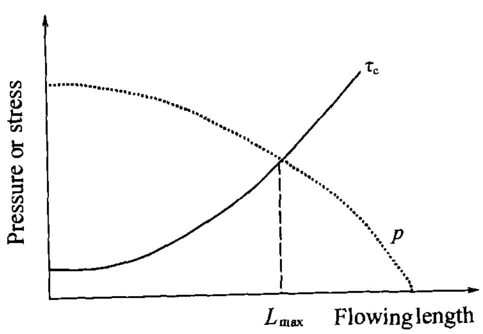

Figure 1 Influence of the flowing length on efficient pressure and critical stress.

In fact the limit flowing length of semisolid slurry is relative to the dimensions of flowing channels. The larger the section area of flowing channels, the smaller the loss of pressure and temperature during the flowing process, and therefore the longer the limit flowing length. As a result, the SFL rule is an equivalence of the maximum flowing section area rule.

In usage of the SFL rule, it is important to know the effects of process factors and slurry factors on the limit flowing length. An equation to determine the limit flowing length L_{max} of slurry with a critical stress τ_c flowing through a circle pipe with radius R acted by the pressure p_j has been theoretically and experimentally deduced by S.M. Xing and L.Z. Zhang [5], shown as:

$$L_{max} = \frac{p_j}{2\tau_c} R \tag{1}$$

From equation (1), it is seen that the limit flowing length is relative to the filling section dimension which is controlled mainly by forming situations for a work piece. So, to a work piece, both of the length to fill and the limit flowing length are different with the forming situations. For a simple example, when a cuboid work piece of 500 mm long, 200 mm wide, and 50 mm thick, is indirectly pressed to form, the length to fill and the area of the flowing channel section at a horizontal forming place is respectively 250 mm and 250 cm^2, which is 1 time smaller and 2.5 times larger respectively than those at a vertical forming place shown as the **figure 2**. As a result, it is confirmed that the work piece formed at a horizontal forming place is more fine and complete than at vertical forming place.

Moreover, from equation (1) it is seen that the limit flowing length is relative to the critical stress of the slurry. Because the critical stress is controlled by stain rate, which is controlled by the filling speed of the slurry, a fast filling speed is benefit to obtain a complete work piece. So high pressing velocity of the punch in the semisolid rheologic forging process is popular in industrial production.

2.2 Pressure filling (PF) rule

Most advantages of the semisolid processing are resulted from the action of pressure on the slurry [6, 7]. However, there are two different periods in the actual process, one is named pressure filling, the other is named naturally filling or filling without pressure. The former is in the stage from the time when the punch touching the slurry to the time when the slurry solidifies completely, in which the slurry filling process is continually acted by a pressure. The later, filling without pressure, exists in the beginning stage from the time when the slurry is just poured into mold to that time when the punch is contacted with the slurry. In the naturally filling process, the force making slurry flow is only the gravity which is not large enough to make the slurry flow and to fill the mold well. As a result, the macrostructure of the work parts in naturally filling is the same as that in the traditional casting process. However, in the pressure filling stage, the slurry is filled into the mold acted by a high pressure all the time so as to form a complete and perfect work piece. Therefore, in a semisolid forge process, to shorten the naturally filling stage as much as possible is a basic rule, namely the pressure filling rule (PF rule).

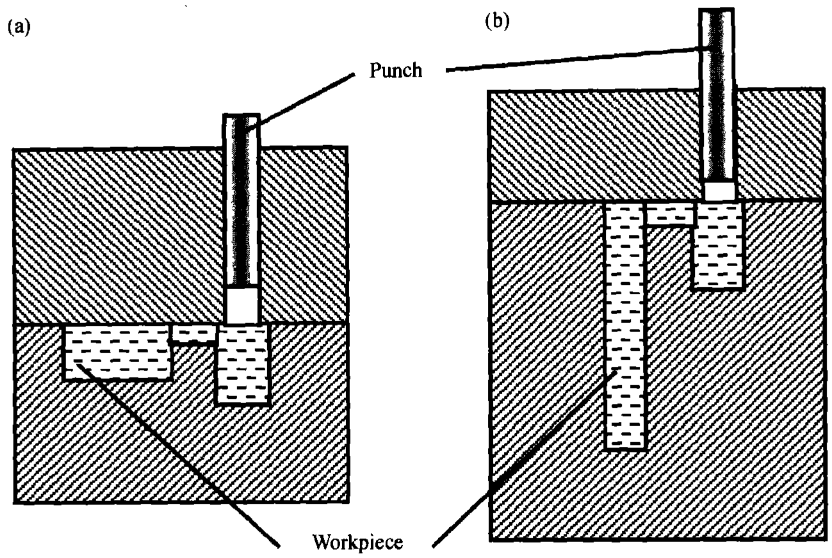

Figure 2 Comparison of different forming situations: (a) horizontally forming; (b) vertically forming.

There are two kinds of pressing modes, directly pressing mode and indirectly pressing mode as shown in **figure 3**, in the semisolid rheologic forging process. In order to avoid naturally filling mold, it is necessary to select a rational press mode. In the directly pressing mode, the semisolid slurry is first poured into the bottom of the mold cavity and solidified and formed without pressure. However, in the indirectly pressing mode, the slurry is poured into a special cavity first, and then is filled into the mold by a pressure, therefore the whole work piece is formed by a pressure. It is for this reason that the indirectly pressing mode is always to be used to produce a complex work piece in the process.

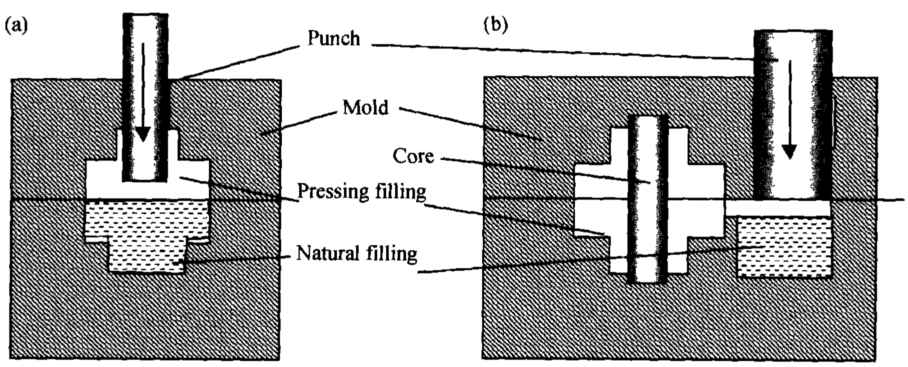

Figure 3 Pressure filling and natural filling: (a) directly pressing; (b) indirectly pressing.

If a work piece has to be formed by the directly pressing mode, the parts with complex shapes of the work piece are filled by pressure as much as possible through rationally selecting the forming place and pressing mode. For example, fine work pieces can be obtained with the forming place as shown in figure 3(a), otherwise the slat of the work pieces cannot be completely formed with the forming place shown as figure 3(b). It is confirmed that the PF rule is another basic principle of the semisolid forging process.

2.3 Rule of the minimum uplifting mold pressure (MUMP rule)

The pressure to uplift mold is a force to make the mold open by a pressure of gas and slurry in the mold. If the pressure is larger than the locking mold pressure of the forming machine, the mold will be separated in the filling mold process and result in some accidents or produce some excrescent constructions. The smaller the uplifting mold pressure in the process is, the larger the power of the forming machine needed is. Therefore, making the uplifting mold pressure minimum is the third basic rule, namely the rule of minimum uplifting mold pressure (MUMP rule).

There are many ways to abide the rule such as making the minimum projection area of the work piece on the plane vertical to the pressing direction, strengthening the exhaust effects and decreasing the flowing velocity of the slurry. In fact, the minimum uplifting mold pressure is proportional to the projection area on the plane vertical to the pressing direction and the pressure acted on the slurry, shown as the following formula:

$$F = pA \tag{2}$$

where p is the forming pressure, A the projection area of the work piece and other additional parts on the plane vertical to the pressing direction.

Actually, the projection area of the work piece and other assistant parts on the plane vertical to the pressing direction is also controlled by the forming situation to a set of work piece. For example, as shown in figure 2, the projection area is 1000 cm^2 when the forming situation of the work piece is horizontal, and it is decreased 10 times and into only 100 cm^2 when the forming situation of the work piece is vertical.

The significance of the rule is not only supplying a foundation upon which one can select the forming machine, but also increasing the forming pressure even without increasing the power of the forming machine and finally improving the quality of the work piece.

3 Additional rules

Based on the above basic rules, there are some additional rules of the process to be abide such as the rules to determine the forming pressure, filling pressure and locking pressures.

3.1 Rule to determine the filling pressure

The pressure for filling mold, filling pressure for short, plays a very important role in the semisolid forging process. When the filling pressure acted on the slurry is smaller than the critical stress, the slurry cannot flow at all. Consequently, in order to make the slurry into the mold, a pressure larger than the critical stress must be acted on the slurry. However, the critical stress of the semisolid slurry is different with the kind of alloy, the micro-construction of the slurry and the temperature of the slurry which is changed in the flowing process [9,10]. So the filling pressure must be larger than the critical stress at the whole filling period. From equation (1), an additional rule to determine the filling pressure is obtained and shown as:

$$p_j \geq \frac{2L_{max}}{R}\tau_c \tag{3}$$

If the actual filling pressure breaches equation (3), the mold cannot be completely filled, and complete work pieces cannot be obtained.

3.2 Rule to determine the forming pressure

The forming pressure, a necessary pressure to form a work piece, is used to compensate the volume shrinkage in the solidification process to prevent the work piece from shrinkage defects. However, the values of the forming pressure are mainly relative to the dimensions of flowing channels. The longer the flowing channels are, or the smaller the flowing channels are, the larger the forming pressure needed is. Moreover the pressure must be large enough to make the solidified shell deform and has to be kept enough time to the end of solidification. Consequently, the forming pressure needed p_b must be larger than not only the critical stress of the slurry, but also the compressing strength τ_s of the solidified shell at the forming temperature. Referring equation (3), the mathematical forms of the rule is obtained as:

$$p_b \geq \frac{2L_{max}}{R}\tau_s \tag{4}$$

It is experimentally proved that if the pressure designed breaches equation (4), some shrinkage defects are seen in the inner of the work piece. So equation (4) is a usable rule to determine the forming pressure of the semisolid forging process.

3.3 Rule to determine the locking mold pressure

In order to prevent the mold from opening in the forming process, an outer pressure has to provide by forming machine to the mold. This pressure is named a locking pressure. Obviously, the locking pressure has to be larger than the uplifting mold pressure in the filling mold process. However, the uplifting mold pressure is changed in the filling mold process as shown in **figure 4**. In the beginning stage (0 to t_1) in which the slurry do not fill full the mold, and the air in the mold is heated by the slurry with high temperature and compressed because of the volume decreasing step by step with the filling, the pressure acted on the mold is increasing slowly. However, at some time t_1 the mold is filled completely and the pressure is suddenly jumped up to a maximum P_{max}, and then slowly down to the forming pressure p_b. After the time t_3, the pressure acted on the mold is continuously fall down to zero with the volume decreasing of the work piece because of the solidification. From the analysis, it is seen that the minimum locking pressure has to be larger than the maximum uplifting mold pressure P_{max}, instead of the forming pressure p_b.

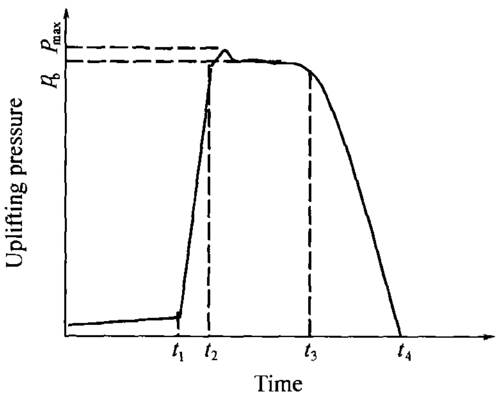

Figure 4 Variation of uplifting pressure with time.

Actually, the maximum uplifting pressure P_{max}, different from the forming pressure p_b, shown in figure 4, is difficult to be accurately determined because it is controlled by many uncertain factors such as the exhaust effects, shape of the mold cavity, filling velocity and fluidity of the slurry. However, the locking mold pressure can be determined experientially, which is at least 1.2-1.5 times as large as the forming pressure p_b, *i.e.*

$$p_{lock} \geq (1.2\text{-}1.5)p_b \tag{5}$$

4 Experiments and discussion

In order to prove the availability of the rules obtained above, a series of experiments was carried on in the Semisolid Forming Laboratory of Beijing Jiaotong University. The work piece selected was the crook tongue, an accessory to connect the carriages of a train, made of C grade steel or A356 aluminum alloy. The forming machine was a THP200 press with a maximum locking force of 2000 kN and a maximum pressing force of 630 kN. The slurry used to form was prepared by a SSC2-30 slurry machine with a maximum content of 30 kg steel. The macrostructure and microstructure of the work piece obtained were checked strictly. The experiments include seven groups are shown in **table 1**. There were 5-7 tests under different conditions in every group. Only one rule of the above six rules was breached in each group. The results obtained are shown in table 1. It is seen from table 1 that all of the experiments has proved the availability of the rules obtained above. If the SFL rule is breached shown as the test group 1, the work pieces obtained are not complete with some deformities, mainly the shut run defects; if the MUMP rule or equation (5) is breached as the tests group 3 and 6, a large unwanted parts on the work piece surface, named fins or veining, is seen in the dividing mold plane which not only increases the material consumption, but also increases the succedent machining cast; and if the PF rule or the SFL rule or equation (3) is breached shown as the test group 1, 2 and 4, some surface defects, such as fins, cold shuts and veinings are seen in the work pieces obtained; if equation (4) is not fitted, some inner shrink defects are seen in the work pieces obtained. Only if the three basic rules and the three equations (3)-(5) are true in the process design and production, satisfying work pieces are obtained shown as group 7 in table 1.

However, the wide applicability of the rules for work pieces with different shapes and of different materials is still necessary to be proved in the future researches and production.

Table 1 Examples of experimental results

Test	Basic rules			Equations			Defects of work pieces
group No.	SFL rule	PF rule	MUMP rule	Eq.(3)	Eq.(4)	Eq.(5)	
1	Breached	True	True	True	True	True	Misruns, shut runs or cold shuts
2	True	Breached	True	True	True	True	Veinings or shut run
3	True	True	Breached	True	True	True	Deformities or thick fins
4	True	True	True	Breached	True	True	Cold shuts or shut runs
5	True	True	True	True	Breached	True	Shrinkage cavities or holes
6	True	True	True	True	True	Breached	Deformities or thick fins
7	True	True	True	True	True	True	Satisfying

5 Conclusions

(1) There are three essential rules respectively named as the shortest flowing length (SFL), the pressure filling (PF) and the minimum uplifting mold pressure (MUMP), and three equations (3)-(5) necessary to be abided in the semisolid forging process design and control. Only when all of the rules and equations are true, a fine and complete work piece can be obtained.

(2) The basic rules and equations obtained are ex-

perimentally proved available. However their wide applicability still needs to be investigated in the scale production.

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