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Mechanics and forming theory of liquid metal forging①

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Abstract: On the basis of steel liquid forging and aluminium alloy liquid forging, liquid metal forging was investigated, such as the assembly model, metal plastic flowing, the force-displacement curves, the harmonious equation, calculation of value of altitude deformation and determination of specific pressure of liquid metal forging. On the basis of the theory of metal plastic forming and the characteristics of liquid metal forging, the achievements on the mechanics and forming theory of liquid metal forging were given out by combining the theory and experiments systematically, and an important preparation for establishing liquid metal forging theory was suggested.

Key words: liquid metal forging; plastic flowing; deformation

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1 INTRODUCTION

In the liquid metal forging process, metal was directly poured into the die cavity, then mechanical static pressure was applied by an oil press which made the unsolidified and quasi-solidified metal flow solidify with little plastic deformation. Because liquid metal or quasi-solidified metal are easy to flow, the process can be carried out with relatively lower consumption of deformation energy. Compared with casting, the way of feeding was changed. In the solidification of liquid metal, the volume contraction would result in the emergence of the shrinking cavity and porosity. While liquid metal was solidified, in the casting process, the shrinkage was fed by utilizing a riser, that is, utilizing the characteristic of directional-solidification, but it was difficult to eliminate shrinkage completely. In the liquid metal forging process, the plastic deformation would make the closed and solidified crust produce altitude and radial directions contraction and forcedly feed the shrinkage. This feeding style was not only easy, but also complete. So it is very significant to study this process[1, 2]. In this paper, on the basis of theory and experiments, the research development in recent years has been given out to establish a new theory.

2 ASSEMBLY MODEL OF LIQUID METAL FORGING

It is very complicated to research the liquid metal forging process, because the plastic deformation, which is a mechanical process, mingles with solidification and formation which are chemical and physical process, especially there exists the solid-liquid zone. So an approximate model was made for the solidifying object of liquid-solid zone and liquid part, which is shown in Fig. 1, and the three constitute a continuous assembly body.

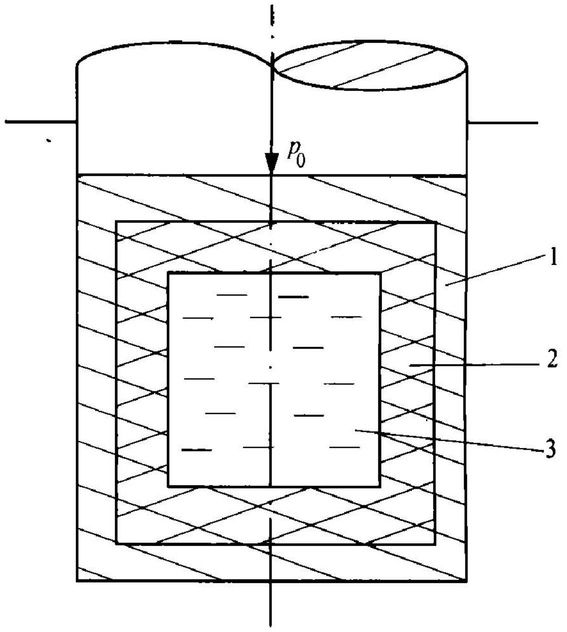

Fig. 1 Model for liquid metal forging assembly body
1 —Solid; 2 —Solid-liquid; 3 —Liquid

2.1 Continuity of assembly

In fact, its continuity is expressed by the temperature distribution. Because the temperature gradient is relatively large, the state of metal is probably liquid, solid-liquid or solid in different temperature fields. The alteration of metal existing states actually

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shows that the metal microstructure is altered. The metal microstructure may transit from SRO (short range order) to LRO (long range order) or LRO to SRO. The existing states don't change suddenly but continuously. Therefore, the assembly body is continuous and homogeneous.

2.2 Mechanical feature in three different areas of assembly body

The solidified area is almost a homogenous and continuous deformed object in the liquid metal forging process, its volume expands from the smaller to the larger. At last, it completely substitutes for the solid-liquid zone and liquid part, the microstructure gained is dense, with no shrinkage cavity.

During the transforming process from liquid state to solid state, it has been considered that the plasticity in solid-liquid zone was approximately zero where the temperature was several degrees higher than the solidus, and it reaches maximum value where the temperature was several degrees lower than the solidus[3]. From high plastic state to brittle state, it doesn't take place suddenly, there exits a brittle temperature range. The reason is that: when the temperature is higher than the solidus, the crystalline framework has been bound together, which separates the remained liquid into flakes situated at the grain boundary. The ability to endure plastic deformation for this kind of microstructure was very low. As soon as it was applied by tensive stress, the liquid layer along the force direction could decrease its height and be pulled longer along the force direction, some plastic deformation could be produced; but the liquid layer which was vertical to the force direction was just in opposite condition. It can't decrease its height and be pulled longer along the force direction. So the crack along the crystal boundary would arise by pulling. As to the temperature lower than solidus, because the liquid layer between crystal grains has not existed, its plasticity can reach maximum value.

The liquid part is a fluid object. It can flow and deform because of its own mass. Based on the above analysis, it is clear that there is large differences of the mechanical property among solidified crust, solid-liquid zone and liquid part. According to the opinion of rheology, it can be considered that the solidified crust is plastic object, solid-liquid zone is brittle object and unsolidified part is adhesive object (there is a lot of crystal neucleations in it). Thus, plastic object, brittle object and adhesive object constitute the continuous assembly.

2.3 Mechanical behaviors of assembly

The mechanic behaviors occur from outside to inside in liquid metal forging process. There occurs plastic deformation in the solidified crust, and appears crack in solid-liquid zone; the liquid part was just squeezed into microcrack under the application of the isostatic pressure, at the same time, the plastic deformation object extended itself as crystallizing and solidifying. The solid-liquid zone also extended, owing to the smoothing of temperature gradient, and only the liquid part was decreased gradually. Until some time, the liquid part has completely changed into solid-liquid zone. Then the assembly changed into a plastic and brittle assembly which was constituted by the solid crust and the solid-liquid zone. If the plastic deformation in solidified area can occur continuously, compressive stress could completely overcome the destructive condition of the brittle object and the tension stress was caused by volume contraction of the liquid flake. At last, the assembly changes into a unitary plastic object, the liquid metal forging process was finished.

3 METAL PLASTIC FLOWING IN LIQUID-METAL FORGING

After the molten metal was poured into the die cavity, an unclosed crust would be formed. As the punch went down, the two following processes would begin as soon as the punch contacted the molten metal[4, 5]:

1) the molten metal near the punch began to form solidified layer, which linked up with peripheral crust to make up a closed crust, and the closed crust become thicker and thicker;

2) the unsolidified metal was compressed and the mechanic conditions of crystallization and solidification under high pressure were formed.

Apparently, the first process was a solidifying one. The crust was thicker and thicker and the unsolidified metal surrounded by the crust became less and less, until the process was finished. The second process was a mechanic one. It concerned how to transmit pressure to the unsolidified metal and made it endure isostatic pressure, and kept this situation through total process. It is most important for the semisolid and solid metal to produce various plastic flowing behaviors.

1) Fundamental styles of plastic flowing of metal during the liquid metal forging process

At the initial stage of liquid metal forging, the main style of metal plastic flowing is that the closed crust was bent along the altitude direction, which would eliminate interval between crust wall and die wall. Metal plastic flowing is mainly expressed by decrease in its height (shown in the Fig. 2) to feed the shrinkage cavity caused by liquid-solid contraction in the solidified front in Fig. 2, the rigid plastic zone can be divided into two parts, the strong PF zone 1 and the weak PF zone 4. Supposing that there exists a temperature range in solidification field, thus there is a solid-liquid zone which is a closed and curved strip. Its width is decided by the size of crystallizing range, and it is always carried toward the center of workpiece as solidifying. If there is no shrinkage cavity in solidifying strip, the solidifying zone 2 will undertake the pressure transferred from the rigid-plastic zones 1, 4 and central liquid zone 3.

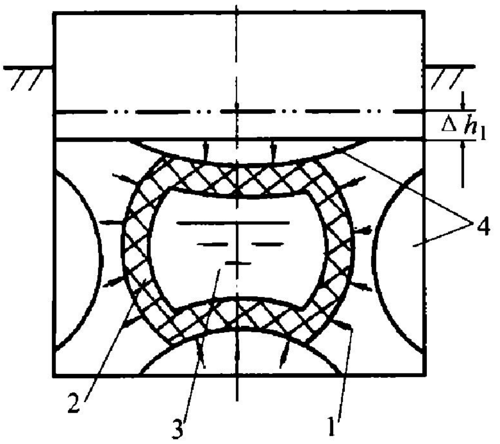


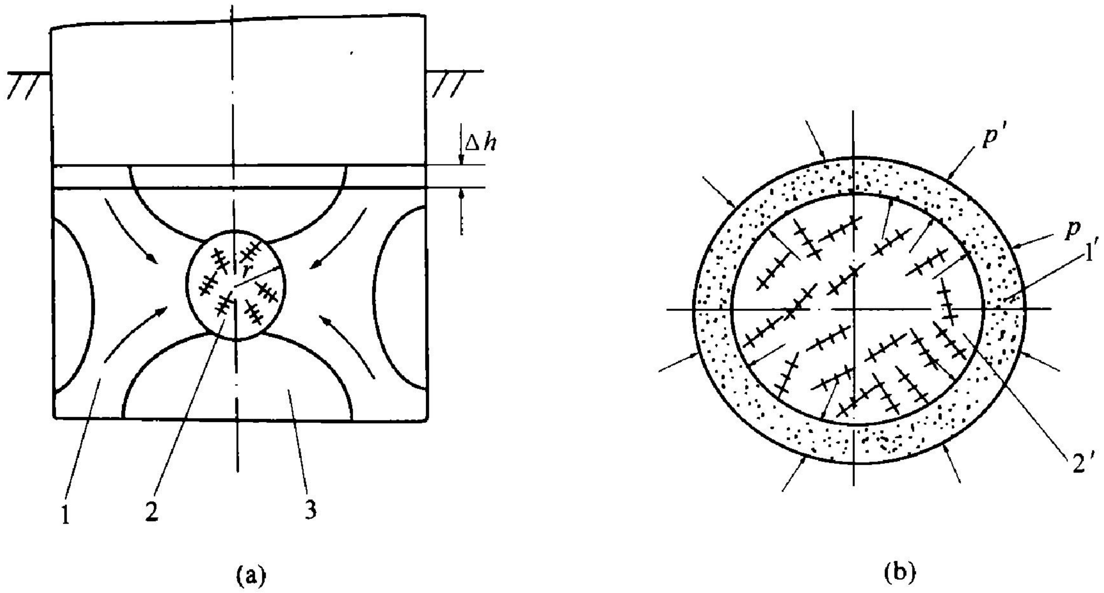
Fig. 2 Fundamental styles of metal plastic flowing in liquid metal forging process
1 —Strong plastic flowing area; 2 —Solid area; 3 ——Liquid area; 4 —Weak plastic flowing area

At this time the metal plastic flowing will stop. As soon as the contraction produces dendrific gap, the pressure in the liquid zone 3 is reduced instantly. Because the pressure in liquid zone 3 is transmitted by solidifying zone, if the gap emerges, the transmitting pressure zone will cause the plastic flowing and push the solidifying zone to center. Then the volume of the solidifying strip decreases, the central liquid zone undertakes isostatic pressure and the new mechanic equillibriums are established.

On the analogy of these, the solidifying zone will continuously solidify, the rigid-plastic zone will increasingly produce plastic flowing to the center, the solid-liquid strip will also carry toward center constantly, and the pressure in the liquid zone will be increased and decreased in turn. All those have formed the force transmission and energy consumption, which constitute the fundamental styles of metal plastic flowing in the liquid forging process.

2) Metal plastic flowing styles at last stage

What is called the plastic flowing at the last stage is that the liquid zone 3 disappears and the solidifying strip becomes a globe whose radius is r (shown as Fig. 3(a)). The temperature of the isothermal camber (the surface of the globe) is T_B, the central temperature is T_A. So the temperature gradient is $(T_A - T_B)/r$. At this time, the unsolidified part is in the mushy state and its characteristic is in-homogeneous and brittle, meanwhile, its shrinkage cavity is filled up else by decreasing its height and making plastic deformation occur in the rigid-plastic zone. In fact, there also exists a globe crust strip with porosity. The difference from the former is that the central globe is not liquid phase but liquid-solid phase. The mechanic illustration is shown in Fig. 3(b), where, p is decided by the deformation resistance in the rigid-plastic area and p' is decided by the deformation resistance in brittle object 1. The stress deviator $(p - p')$ is the power which results in the globe crust in plastic flowing. The metal plastic flowing in the rigid-



(a) (b)

Fig. 3 Plastic flowing (a) and mechanic illustration(b) at last stage
1 —Strong plastic flowing area; 2 —Weak plastic flowing area; 3 —Solid area; 1′ —Solid area; 2′ —Liquid-solid area

plastic zone is shown in Fig. 3(a). The volume of the globe will become smaller and the brittle object will be densified continuously, until solidification is finished.

After that, the solidified object changes into the rigid-plastic object. If the pressure is remained, the plastic flowing of dense metal will continue until the body is completely solidified.

The assembly of the plastic object, the brittle object and the viscous object will be altered into the assembly of the plastic object, and the brittle one at last stage. In order to fulfill shrinkage completely, the deformation in the plastic object will be necessary which can make the brittle object dense. The metal flowing features can be observed from Fig. 4. The pattern of the microstructure in Fig. 4(a) is mud-rock riverbed-like. Fig. 4(b) shows the microstructure of a cinder mouth of red copper which is like whirlpool.

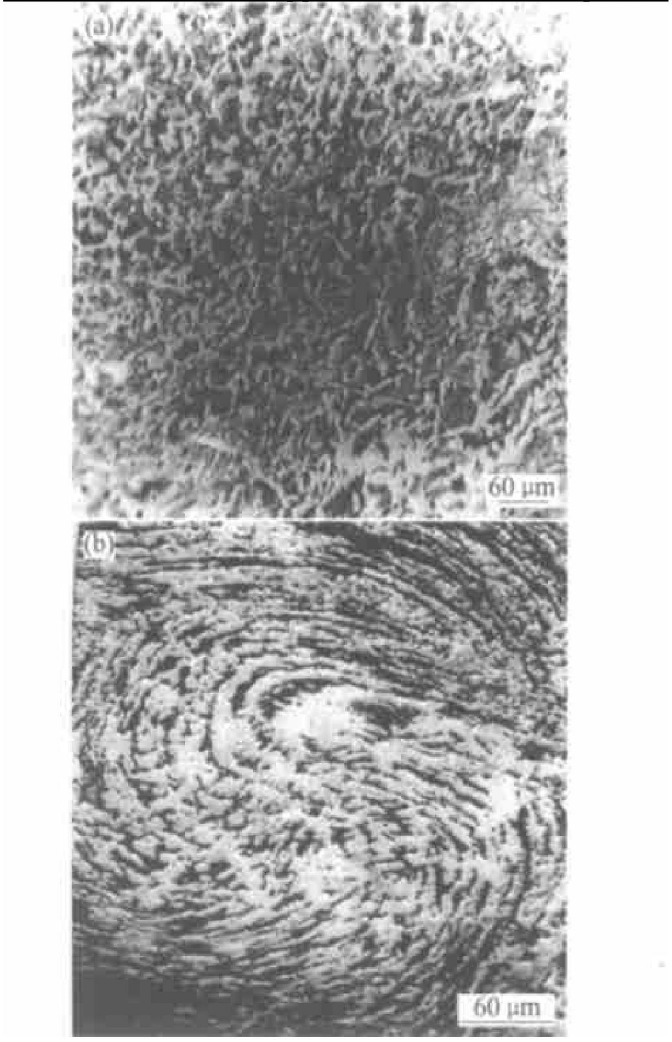


Fig. 4 Microstructures showing the metal flow produced by liquid metal forging.
(a) —30Mn wear-resistant cushion;
(b) —Cinder mouth of red copper produced by liquid metal forging

4 FORCE- DISPLACEMENT CURVES OF LIQUID METAL FORGING

The external features of the mechanic process of liquid metal forging are expressed by the reduction in height. Accompanied by the reduction, the total force was also changed. Fig. 5 shows the experimental force-displacement curve of liquid metal forging of steel. For different materials, the curves are similar. According to the curves, the pressuring process can be divided into two stages: raising pressure stage and maintaining pressure stage. At raising pressure stage, the curve is a conic section of a concave curve. Pressure increased with the raising displacement. This duration was very short, about 4~6 s. Then it is the pressure duration stage. At this stage, the force displacement curve fluctuated under a constant pressure, but the displacement went[6, 7].

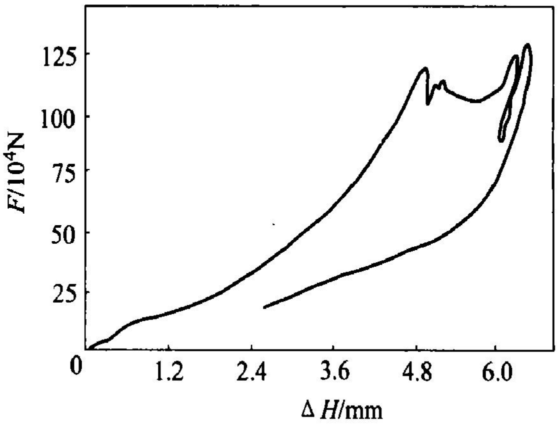


Fig. 5 Force-displacement curve of liquid metal forging of steel at specific pressure of 40 MPa, pressure duration of 20 s

When the pressurizing punch passed through the solid film of molten metal in cavity (pressurizing with complex punch) and stepped into molten metal, the metal would flow in the opposite direction of the punch movement and filled up the cavity. As soon as the action was finished, the pressurizing process would begin at once.

At the initial stage of pressurizing, there was some interval between the outside wall of products and die wall, and the temperature at the surface of the liquid metal was higher, the crust was formed later. So when the pressure was applied, the large displacement of deformation can be obtained under a lower pressure. This is why the mechanic phenomenon is manifested at the early pressurizing stage.

When the outside wall of product attaches to the die wall, the upper and lower surfaces of the product also separately attached to the bottom of punch and the die cavity bottom under the action of the vertical pressure, the raising pressure stage was finished, the pressure duration stage began. At this time, the action of pressure was to keep the mechanic behaviors going on. The continuous increase of displacement manifests that the shrinkage cavity has been filled up.

The finishing mark of solidification is the ending of feeding of the press punch. Then, the increment of displacement will approach to zero. The pressure duration stage can be ended also. If the pressure is continuously applied, the densifying process will occur. But, the increment of displacement is very low, the larger the external pressure is, the more apparent the densifying process is.

5 HARMONIOUS EQUATION OF LIQUID METAL FORGING

The pressure is applied by a hydraulic press for the liquid metal forging. In order to ensure the molten metal to solidify under the isostatic pressure and gain qualified products, there must be some relationship between the downward velocity of the punch and the solidifying speed in the liquid metal forging process. The relation equation between the downward speed u and the crystal solidification speed v can be deduced as

$$u=\frac{1}{A}v \tag{1}$$

where A is the contact area between the product and the lower end of punch. Through transformation, Eqn. (1) can be written as

$$u=\frac{k_1k_2}{\sqrt{t}} \tag{2}$$

where k_1 is solidification coefficient, for metal die casting steel, $k_1=2.6$; k_2 is correction coefficient of liquid metal forging, $k_2<1$; t solidification time.

It can be seen from above equation that the pressing speed is inverse ratio to the square root of solidification time. It reflects the quantitative relationship between plastic deformation and solidification in the liquid metal forging process. The connection between the metal solidification and the forging machine parameter has been established by it yet. Fig. 6 shows the pressing experimental speed- time curve obtained from liquid aluminium alloy forging, which coincides with the theoretical curve.

6 CALCULATION OF VALUE OF ALTITUDE DEFORMATION FOR LIQUID METAL FORGING

The plastic deformation of liquid metal forging can be expressed by the strain in plastic theory[10, 11].

According to the law of mass conservation, it is easy to obtain:

$$\varepsilon_h=\varepsilon_v-(\varepsilon_r+\varepsilon_\theta) \tag{3}$$

where ε_h is axial strain; ε_r is radial strain; ε_r tangential strain; ε_v real volume strain.

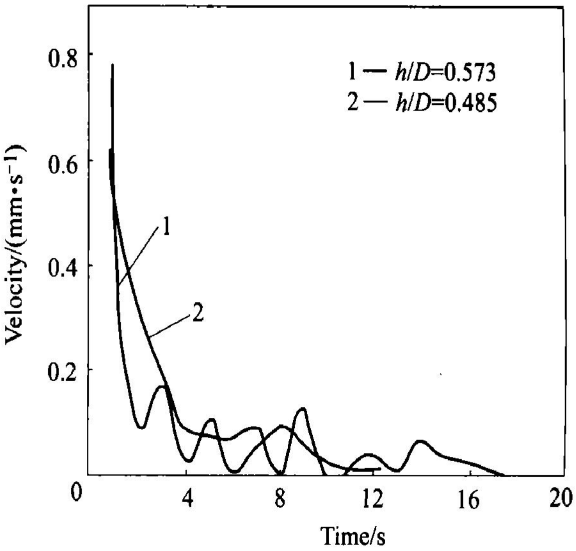


Fig. 6 Relation curve of pressing velocity and time

It can be obtained by deducing that

$$\varepsilon_v=-(0.5+K) \tag{4}$$

$$K=[\alpha_{v,\mathrm{ld}}(t_{\mathrm{pt}}-t_{\mathrm{sn}})+\varepsilon_{v,\mathrm{sn}}-0.5]/[1-\alpha_{v,\mathrm{sm}}(t_{\mathrm{sn}}-t_{\mathrm{od}})] \tag{5}$$

where $\alpha_{v,\mathrm{ld}}$ is volume contraction coefficient of the molten metal; $\alpha_{v,\mathrm{sm}}$ is solid contraction coefficient, $\alpha_{v,\mathrm{sm}}=4.2\times10^{-6}$ for the low carbon steel above 1 000 ℃; t_{pt} pouring temperature of molten metal; t_{sn} solidification temperature of the molten metal; $\varepsilon_{v,\mathrm{sn}}$ volume contraction ratio for the molten metal when it has solidified completely.

Substitute Eqn. (4) into Eqn. (3), the theoretical calculating formula for strain in height is gained:

$$\varepsilon_h=-(0.5+K+\varepsilon_r+\varepsilon_\theta)$$

Here, K can be calculated, ε_r and ε_θ can be got by experiments, so ε_h can be known .

The real value by using Eqn. (6) to calculate the deformation is more useless than that of the theoretical conception revealed by it. This formula prompts us that there are three processes occurred in the liquid metal forging process, alteration of its own density of studying object, volume alteration in the transformation from liquid to solid, and the contraction and densifying porosity in solid phase. Apparently, the strain in liquid metal forging is different from the strain conception in plastic theory.

7 DETERMINATION OF SPECIFIC PRESSURE OF LIQUID METAL FORGING

How to connect the specific pressure with product quality directly is getting attentions. Because the specific problem relates to the machine capacity, manages also care this problem. Here, on the basis of different conditions, the slab method and energy method have been used to solve it. This paper only studies the state of solid-liquid.

To the plastic deformation of a solid-liquid assembly, studies are mainly concentrated on the plastic deformation of the solidified crust. Assuming the hard layers adhering to the punch and to the bottom of the die cavity can be separately considered as a part of the punch and the die cavity. The deformation object can be simplified as an annular shape, as shown in Fig. 7.

1) Neutral line at R_0

In this situation, there is no interval between the object and the die wall. Owing to the existence of shrinkage cavity, the molten metal doesn't undertake isostatic pressure, that is, $p' = 0$. It is similar with a ring upsetting (Fig. 7(a)). Utilizing the slab method, the results are got as follows:

Total deformation force:

$$F_0 = \pi\sigma_s\left[R_0^2 - r_0^2 + \frac{2u}{3h}(2R_0^3 - 3R_0^2 r_0 + r_0^3)\right] \tag{7}$$

The specific pressure:

$$p_0 = \sigma_s\left[1 + \frac{2u}{3h}\left(\frac{2R_0^3 - 3R_0^2 r_0 + r_0^3}{R_0^2 - r_0^2}\right)\right] \tag{8}$$

2) Neutral line at r_0

Total deformation force equals (Fig. 7(b))

$$F_0 = \pi\sigma_s\left[R_0^2 - r_0^2 + \frac{2u}{3h}(2R_0^3 - 3R_0 r_0^2 + r_0^3)\right] \tag{9}$$

The specific pressure equation:

$$p_0 = \sigma_s\left[1 + \frac{2u}{3h}\left(\frac{2R_0^3 - 3R_0 r_0^2 + r_0^3}{R_0^2 - r_0^2}\right)\right] \tag{10}$$

Eqns. (8) and (10) have given out the analyzing solution of the specific pressure for solidified crust deformed. The presuming condition is that molten metal does not endure isostatic pressure in the total process of liquid metal forging, in other words, the external pressure is just to guarantee the plastic ring to produce plastic deformation and to fill shrinkage cavity, which consumes all of deformation energy, the pressure on the molten metal transmitted by plastic ring is zero. Of course, it is clear that from the equation that the analyzing solution is instantaneous, it increases when the solidification boundary moves to the center. In pressure duration stage, it can be known by the analysis of the force-displacement curve that the external pressure is constant. This is to say, the sum of the deformation energy consumed on the annular crust and the energy to maintain the isostatic pressure in the unsolidified part is a constant value. Because the former is a constant value, but the latter is not. Therefore, presuming that during the initial stage of liquid metal forging, the external pressure is totally exerted on the molten metal and the plastic deformation energy is zero; during latter stage the external pressure is consumed totally on the deformation energy of the hard crust. According to this presumption, taking $r_0 \to 0$ in Eqns. (8) and (10), the analytic solution of unit deformation force is equavalent to the specific pressure of liquid metal forging.

Eqn. (8) can be rewritten as

$$p_0 = \sigma_s\left(1 + \frac{4u}{3}\frac{R_0}{h}\right) \tag{11}$$

Eqn. (10) can be rewritten as

$$p_0 = \sigma_s\left(1 + \frac{2u}{3}\frac{R_0}{h}\right) \tag{12}$$

Eqn. (12) is the same as the formula calculating the forging pressure of cylinder upsetting, but the calculation result from Eqn. (11) is larger

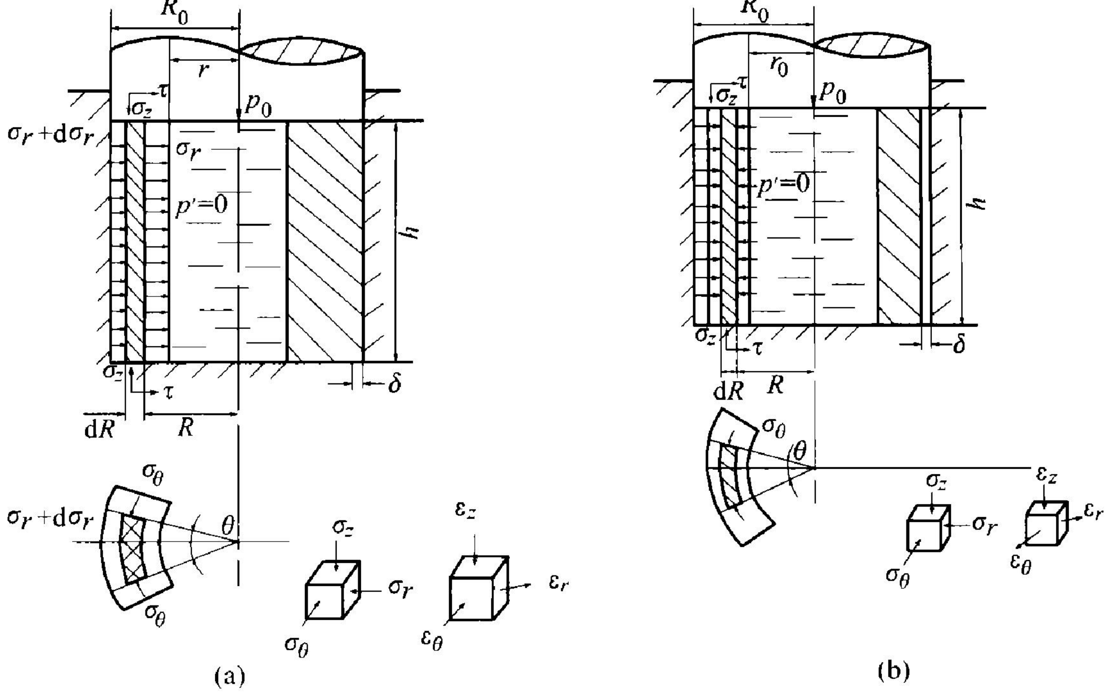


Fig. 7 Strain-stress analysis for solid-liquid assembly
(a) —Neutral line at R_0; (b) —Neutral line at r_0

than that from Eqn. (12). This shows that when solidification is closed to the end, the energy consumption is also large. Though the die cavity is filled by the molten metal, which only needs very small energy consumption, unlike the die forging, which consumes a lot of energy because the hot metal is unsettled and squeezed. Liquid metal forging, also needs large energy consumption at the last stage, in order to eliminate shrinkage cavity and porosity.

8 CONCLUSIONS

1) The presumption of the assembly object reflects the internal situation of the liquid metal forging correctly. It not only includes plastic object with plastic deformation, but also includes liquid and liquid-solid phase with changeable volume and density. On the basis of the presumption, various mechanical behaviors of the metal under liquid forging have been analyzed.

2) The plastic flowing in the liquid metal forging process is different from that in the plastic working. On the basis of the assembly conception, the main plastic flowing styles of liquid metal forging and their experimental observation are given out.

3) The harmonious equation of liquid metal forging expresses the quantitative relationship between plastic deformation and solidification, that is, the pressing speed of the hydraulic press or the punch is inverse ratio to the square root of solidification time. The result is proved by experimental curves. Its significance lies in that it has connected the casting solidification with the parameters of forging machine successfully.

4) By adopting the slab method of plastic theory, the specific pressure for solid-liquid assembly model has been deduced theoretically. When the solidifying zone is approaching to zero, the deduced formula is the same as that of the cylinder upsetting in plastic working. Viewing the situation as a whole, in the last stage of liquid metal forging, the consumption of deformation energy is also large, but its mean value is much less than that of die forging. This result has been proved by the experimental force-displacement curves.

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