A Trial on Direct Forming with Vibration*

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A new metal forming method in which metal material (99.7%Al) is solidified with vibration and directly formed at high temperature is tried. By this method a material which consists of fine and uniform crystalline grains is obtained. The refinement and uniformity of crystalline grain in solidification process are most significant in this Direct Forming. Mechanical properties of formed material are improved to some extent. Therefore it is clear that high quality material can be obtained by this energy-saving and process-saving method.

Key Words : Casting, Forming, Solidification with Vibration, Composite working, Energy saving, Refining of crystalline grain

1. Introduction

In usual metal forming, many working processes are necessary for the purpose of

(a) Usual Process

(b) Direct Forming with Vibration

Fig.1 Characteristics of Direct Forming with Vibration (in case of Aluminum)

recrystallization and refinement of crystalline grains. The temperature and working processes are shown in Fig.1 (a). It is found that crystalline grains are refined and made uniform if vibration is applied on the solidifying metal. And if inside surface of the mold is made of appropriate material and heat flow from the surface is properly controlled, control of solidifying process will become possible. When this control of solidification is established, several working processes after the solidification can be saved. In this study, therefore a new metal forming method in which the metal is solidified with vibration and directly formed in high temperature is tried. This process is shown in Fig.1(b). Characteristic of this new metal forming is that the process is simplified and energy is saved because reheating process is not necessary. In this study this method is tried using pure aluminum (99.7%Al) without grain refiners. Crystalline structure after forming, forming load and mechanical properties of the formed material are examined. Effects of vibration during solidification and vibration during forming are investigated. And advantages of direct forming are discussed.

2. Experimental Equipment

Equipment for casting with vibration and equipment for forming with vibration are used in this trial, as shown in Fig.2. Temperature of the molten metal is kept at 700°C in a heat retaining ladle and degasification (dehydrogenation) is made with hexachloroethane. Then the melt is poured into the mold which is set on the vibrating table. Horizontal circular vibration is applied on the mold during the solidification. Unbalanced mass set on the table is revolved by a DC motor connected with a flexible shaft. The vibration frequency is 50 Hz and the vibration amplitude is 0.25 mmp-p. Horizontal circular vibration consists of only a rotational component and has no rotational component. The mold is made of mild steel 60mm inside diameter and 80mm outside diameter. When

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Fig.2 Experimental method for Direct Forming with Vibration

clay powder is thinly spread on the inner wall to prevent seizure, the mold is called steel mold. And when clay powder is thickly spread on the inner wall, the mold is called porous clay wall mold. Equipment for forming with vibration consists of a container, a punch, a vibrating table, an electromagnetic vibrator, a hydraulic cylinder and flame. Shapes of the container and the punch are shown in Fig.3. Axial-symmetrical product which has H shape section is obtained. In this forming, ingot is pressed by the first punch and then pressed into the end of the container by the second punch. Load is lighter in this forming method compared with the case that ingot is pressed by a single stand punch. Container is heated by sheath heater and the temperature is kept constant (500°C at 36 mm outside from the inside surface of the container). Electromagnetic vibrator is supplied 3 phase current and vibrates the table in horizontal circular direction. The vibration frequency is 100 Hz and the vibration amplitude is 0.1 mm p-p. Forming load and punch stroke are detected by a load cell and a displacement meter respectively.

3. Experimental Method

In order to compare direct forming with usual forming, experiments are made as follows.

(1) Usual forming: Aluminum is solidified in steel mold with no vibration and naturally cooled to room temperature. Then the ingot is reheated to high temperature and formed with no vibration.

(2) Direct forming: Steel mold or porous

Fig.3 Forming dies for Direct Forming with Vibration

clay wall mold is used as a mold. Aluminum is solidified with vibration or with no vibration. Ingot is set in the container at high temperature and formed with vibration or with no vibration.

Experimental conditions are shown in Table 1. The experimental material is 99.7% pure aluminum without grain refiners. Casting temperature is 700°C and forming temperature is 460°C. Lubricant used in forming is graphite mixed with oil. Maximum forming load is 150 kN. Temperature process in usual forming and that in direct forming are shown in Fig.4. In case of usual forming, solidified ingot is naturally cooled to room temperature and reheated in 500°C atmosphere without any mechanical treatment. Then the ingot is set in the container and formed at 460°C. This temperature process is the same as in usual process. In usual

process, the outside surface of the ingot is cut out to eliminate the chill structure at room temperature. In case of direct forming, temperature of the solidified in-

got is about 520°C when the ingot is taken out from the mold, then the ingot is set in the container and formed at 460°C. The time spent for all the processes is short.

Table 1 Experimental conditions for Direct Forming with Vibration

Material: 99.7%Al

(a) Usual Forming

-Ingot is cooled to room temperature, and then reheated and formed-

Casting condition

Mold: Steel Mold 60mm inside diameter

Casting temperature: 700 C

Vibration condition: no vibration

Forming condition

Forming temperature: 460 C

Lubricant : graphite in oil

Maximum Load : 150 kN

Vibration condition: no vibration

(b) Direct Forming

-Ingot is directly formed at high temperature-

Casting condition

Mold: (I) Steel Mold 60mm inside diameter

(II) Porous (clay) wall mold 60mm inside diameter (Clay is spread thickly inside the Steel Mold)

Casting temperature: 700 C

Vibration condition: (A) 50Hz vibration 0.25mm-p

(B) no vibration

Forming condition

Forming temperature: 460 C

Lubricant: graphite in oil

Maximum Load: 150 kN

Vibration condition: (A) 100Hz vibration 0.1mm-p

(B) no vibration

4. Experimental Results

4-1. Crystalline structure after forming

Metallographic macrostructures of the material after solidification and those after forming are shown in Fig.5. Vertical section and cross section of the ingot, vertical H shape section and horizontal section of the formed material are shown. There are 4~7 samples in the same condition but they show almost the same structure, each typical one being shown in this picture. In case of usual forming, the structure which is solidified in the steel mold with no vibration (i) consists of completely columnar grains. There is no equiaxed grain. After the ingot is formed, the structure (a) consists of also columnar grain flows. The width of grain flow is large. In case of direct forming, the crystalline structure which is solidified in a steel mold with no vibration (b) is the same as that in usual forming. Accordingly, there is no influence on the formed crystalline structure of the difference in temperature process. The structure formed with vibration (c) is also the same as that in usual forming. Therefore vibration in

(a) Temperature Process in Usual Forming (measured value)

(b) Temperature Process in Direct Forming (measured value)

Fig.4 Temperature process in the experiments

Fig.5 Effect on grain refinement of Direct Forming with Vibration

the forming process does not influence the crystalline structure.

On the other hand, the crystalline structure which is solidified in the steel mold with vibration (ii) has equiaxed crystalline grains in the central area and crystalline grains are refined. Direct formed structure (d) consists of refined and uniform crystalline grains. The width of grain flow is smaller than that of usual formed material. Structure solidified in the porous clay wall mold with vibration (iii) consists of completely refined equiaxed crystalline grains. The grain size is very small. Its direct formed structure (e) consists of very refined uniform crystals. The width of grain flow is very small. Therefore, refinement of crystalline grains in solidification process is most significant in the grain-refinement of formed material. Refined crystalline structure also can be obtained when the material is solidified in the porous clay wall mold with vibration, cooled to room temperature, reheated to high temperature and formed. Therefore a difference in temperature process does not influence the crystalline structure of formed material either when the structure after solidification consists of refined equiaxed crystals.

4-2. Forming Load

Relation between forming load and

punch stroke in direct forming in which the ingot is made in a porous clay wall mold with vibration and formed with vibration is compared in Fig.6 with that in usual forming. In the first forming, both graphs show the same shape and the same value. Although they are different in crystalline structure, temperature process and vibration condition during forming process, they show the same forming load. The reason why the load increases rapidly at the stroke 40 mm is as follows. When the ingot is upset to the stroke 40 mm the part of material pressed out to the outside area touches the inside surface of container. Friction between the material and the inside surface of container occurs and the forming load increases rapidly. In the second forming, load-stroke curves show various shapes because the material is bitten between punch and container. Comparison between the loads when material is formed with no vibration and when formed with vibration is made in Fig.7. There is no difference between them. Vibration during forming process does not influence the forming load. It is not proper to compare Fig.6 with Fig.7 because their measuring times are too much separated and measuring conditions are different.

4-3. Mechanical properties of the formed material

Fig.6 Effect of Direct Forming on the Relation between Load and Stroke

Fig.7 Effect of Vibration during Forming on the Relation between Load and stroke

Table 2 Mechanical Properties of Direct Formed Materials

Material: 99.7%Al, Casting temperature: 700°C, Forming temperature: 460°C

Experimental conditions					Radius direction			Circular direction		
Forming method	Mold	Vibration condition in casting	Vibration condition in forming		Proof stress Mpa	Tensile strength Mpa	Elongation %	Proof stress Mpa	Tensile strength Mpa	Elongation %
i) Usual Forming	Steel Mold	no vibration	no vibration		41.3	60.4	36	42.7	69.1	42.5
ii) Direct Forming	Steel Mold	no vibration	no vibration		47.0	68.7	35	44.1	70.1	36.5
iii) Direct Forming	Steel Mold	no vibration	vibration		44.4	67.5	36.5	45.3	69.1	35
iv) Direct Forming	Porous (clay) wall mold	vibration	vibration		42.6 [ⓐ]	71.0 [ⓐ]	48.5 [ⓐ]	44.5 [ⓑ]	74.7 [ⓑ]	47 [ⓑ]

Number of samples: i) 4 ii) 2 iii) 2 iv) ② ③
 1 Mpa=0.102kgf/mm²

Tensile properties of the formed material are shown in Table 2. Test pieces are cut from the part in circular direction and radial direction in the formed material. Comparing the piece in usual forming (i) and the one in direct forming with vibrated porous clay wall mold (iv), the tensile strength and elongation of the latter are greater than those of former to some extent. And although there are differences between the properties in radial direction and those in circular direction in the former, there are not large differences between them in the latter. To examine the effect of direct forming, properties of the material made in usual forming (i) are compared with those of a direct formed material which has been solidified with no vibration and formed with no vibration (ii). There are no differences between them except in proof stress and tensile strength in radial direction. To examine the effect of vibration during forming process, properties of the direct formed material (iii) are compared with those of a material which has been solidified with no vibration and formed with vibration (iii). There are no differences between them. Although any quantitative difference is not revealed in this test because test pieces are too small and the number of pieces is not sufficient, the mechanical properties (tensile strength and elongation) of the direct formed material which has been solidified in porous clay wall mold with vibration and formed with vibration are better than those of the usual formed material.

5. Investigation

Material which has fine and uniform crystalline grains is obtained in this new metal forming method.

First, effect on the grain refinement in solidification process is investigated. Refinement of crystalline grains in solidification is most important for the refine-

ment of grain size in the formed material. If the grain size in the solidified material is large, that in formed material is equally large in such a forming like this where the forming ratio is small. If refined and uniform crystalline grains can be obtained in solidification process, the formed material also has refined and uniform crystalline grains. Grain refining effect comes from solidification with vibration, but it is promoted if the melt is solidified in porous clay wall mold with vibration. Moreover when the mold is made of water-cooled copper sleeve and porous material (SUMICERAM: $Al_2O_3 \cdot SiO_2$ powder cement) is spread on the inside surface, the solidified structure is more refined as shown in Fig. 8 than the structure obtained in usual forming. But there still remain short columnar crystals in the outside boundary part. And the ingot suffers shrinkage effect of pipe in the top part.

Second, advantage of direct forming (directly formed without cooling and reheating) is discussed. As far as pure aluminum is employed in the experiment, there are no differences in the metallographic structure between direct formed material and usual formed material as shown in Fig. 5. And there are no differences in the mechanical properties of formed material as shown in Table 2. Therefore direct forming does not itself influence the crystalline structure and other properties. So the same material as the one obtained by usual forming can be obtained by this energy-saving method. The solidified structure of some material may change in the reheating process, but direct forming has good effect for retaining the solidified structure to the final structure.

Next, effect of vibration in forming process is discussed. Vibration during forming does not give an effect on crystalline structure or mechanical properties of formed material. Although an effect for decreasing of forming load was expected,

it did not appear in this experiment. The reason is that a relative slip between material and container surface is not produced because the vibrating force is too small or the container and the punch are vibrated together as one block.

One of the features of this new metal forming method is that solidification process and forming process are separated. Liquid metal forming or semi-liquid metal working is known as a method of direct working from casting to forming. But the process of solidification and that of forming are not separated in these methods. So plastic deformation is not given to the material, and the structure does not become a grain flow structure. In this new method, the properties in solidification process and those in forming process are independently acquired.

Following subjects remain for a future study. It is necessary to establish a method of making an ingot which consists of all grain-refined equiaxed structure and has no shape defect (which produces skin inclusion or surface cracking in the subsequent working process). For this purpose, it is necessary to consider the forming technology from the viewpoint of control of solidification process such as directional solidification. In this forming, as the weight of product is the same as

that of solidified ingot, a method to keep the constant weight of the poured melt must be established. To attain the effect of vibration in the forming process, a vibrating method to produce a relative slip between material and container surface is to be tried. Since forming load decreases with an increase of forming temperature, development of heat proofing in die material and control of container temperature are desirable. Not only pure aluminum but also aluminum alloy which will be given precipitation treatment is desirably employed in the experiments.

As an application of this direct forming method, the solidified ingot is directly extruded. The metallographic structure obtained is shown in Fig.9. The material which has been solidified in the steel mold with no vibration and then extruded is composed of long columnar crystalline grains. Structure around the outside area is very different from that of central area, which is apparently observed in the photograph of transverse section. On the other hand, the crystalline structure of the material which has been solidified in porous (SUMICERAM) wall water-cooled mold with vibration and extruded is composed of very refined and uniform crystalline grains. There is no difference

Fig.8 Effect of Direct Forming with Vibration (Die forming)

Fig.9 Effect of Direct Forming with Vibration (Extrusion)

between the structure of axial central area and that of outer area. The distance from the die to the point where recrystallization occurs is short. As above described, direct forming with vibration can be applied to extrusion and other workings.

6. Conclusions

Direct forming with vibration is tried using pure aluminum (99.7%Al) and the results are compared with those of usual forming. The following are made clear from this trial.

(1) If the material is solidified with vibration, the crystalline structure of the formed material consists of refined and uniform grain flows. Especially when it is solidified in porous wall mold with vibration, grain refinement is very much promoted and the formed material is composed of very refined uniform crystals.

(2) Difference in temperature process between direct forming without cooling and reheating and usual forming in which the ingot is cooled to room temperature and reheated does not influence the crystalline structure and mechanical properties of the formed material as far as pure aluminum is used.

(3) Mechanical properties of grain-refined material made in direct forming are better than those of columnar crystalline material made in usual forming in this test.

(4) Vibration during forming does not influence the forming load in this trial.

Therefore, if control of solidification is established, high quality material can be obtained by this energy-saving and process-saving method.

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