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Numerical simulation and experimental study for rheo-forged component using direct and indirect die system

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Abstract: Sand casting and die casting processes have been used widely for complex automotive products such as knuckle, arm, etc. Usually, a part fabricated by casting has limited strength due to manufacturing defects such as the dendrite structure, segregation and porosities. As an attempt to offer a solution to these problems, forging has been used as an alternative process. However, the forging process provides limited formability for complex shape products. Rheo-forging of metal offers not only superior mechanical strength but also requires significantly lower machine loads than solid forming processes. In order to produce semi-solid materials of the desired microstructure, a stirring process is applied during solidification of molten metal. The results of an A356 aluminum alloy sample, which are obtained by experiment and by simulation using DEFORM 3D, are present.

Key words: rheo-forging; A356 alloy; formability; forming defects

1 Introduction

Rheological material forming is a near-net-shape forming process at a temperature between the liquidus and the solidus. Rheological material forming process can decrease segregation by improving fluidity in the globular microstructure state with a flow that does not entrap air. Rheological forming of difficult-to-machine materials is useful because it produces much less strain resistance than the conventional forging process.

However, it is difficult to perform a numerical simulation of the rheological process because of its complicated process. In the rheological process, analysis based on rheological theory allows for a more exact understanding of characteristic of the material.

Rheological material has thixotropic, pseudo-plastic, and shear-thinning characteristics[1]. KANG et al[2] conducted a numerical simulation of mold filling and deformation behavior by using the commercial package MAGMAsoft and a two-phase code. JAFARI et al[3] researched the simulation of thixo forward extrusion process by using finite volume method (FVM). A FVM is suitable for liquid flow processes such as the casting process. However, FVM has a disadvantage of low calculation speed in comparison with the finite element method (FEM).

Therefore, in the present work, the feasibility of applying an FEM simulation is investigated for a complex product in the high solid fraction rheo-forging process. And, possible defects in the rheo-forged product are investigated by simulation and experiment.

2 Experimental

In this study, A356 aluminum alloy was used. To remove the oxidization products and hydrogen gas from the molten metal, nitrogen gas was injected into the melt for 15 min. Oxidization products and impurities were thus cleared away from the molten metal surface[4]. In aluminum alloys, hydrogen gas readily makes holes within the alloy during solidification. In addition, hydrogen gas has the highest solvency in a material among other constituents of air, such as oxygen and nitrogen. Consequently, porosity is increased within the alloy as the temperature is decreased, which degrades the mechanical properties of the alloy[5].

Fig.1 shows a schematic diagram of vacuum casting system. After the molten metal is poured, the injection punch is lowered down and closed. After sleeve is closed by punch, vacuum pump is operated. Gas and air are then discharged from the sleeve. This system prevents both

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the oxidation of the molten metal and air indraft. The remaining hydrogen gas is also extracted within the metal. Knuckles are fabricated by a press machine. To decrease the process cycle time, the direct forging type is required, and Fig.2 shows the schematic of the direct-type experimental procedure in the rheo-forging knuckle sample. However, it is difficult to control the metal flow in semi-solid forming due to overflowing. Overflowing metal prevents the die from closing, and this incomplete closing leads to low formability of the product. Therefore, the indirect-type forging process with a sleeve is needed to complete the filling of a material, as shown in Fig.3. Indirect-type dies consist of upper and lower die and punch. The slurry is poured through the sleeve after closing the die. Then, the slurry is loaded by a punch at a controlled die and punch temperature by a heating and cooling system.

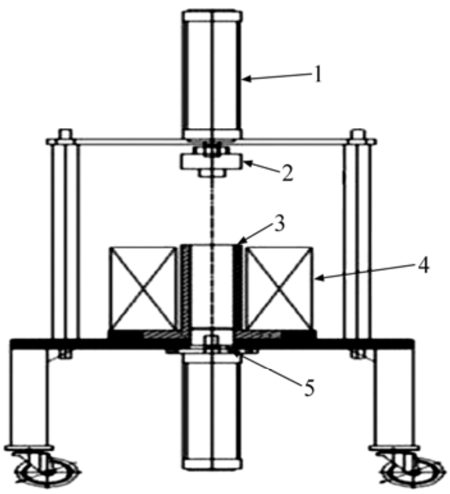

Fig.1 Schematic diagram of vacuum casting system: 1 Air cylinder, 2 Punch; 3 Sleeve; 4 Case; 5 Bottom punch

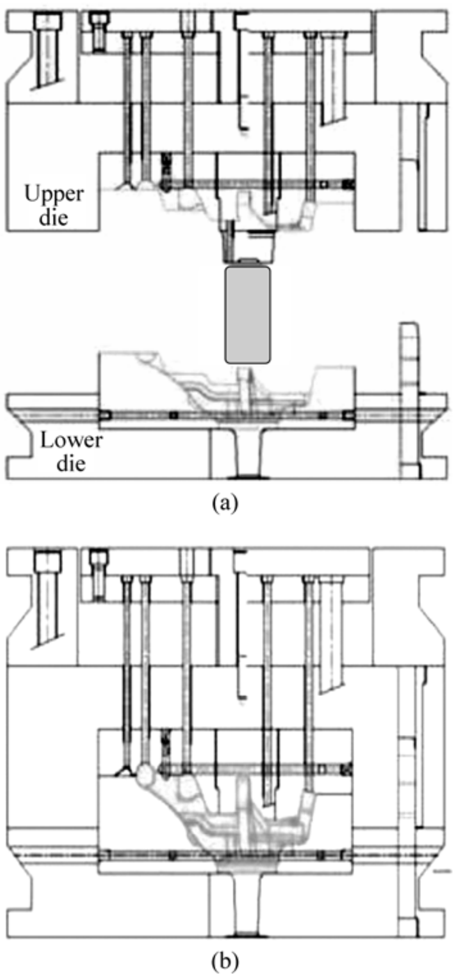

Fig.2 Schematic of direct-type experimental procedure in rheo-forging: (a) Inserting billet; (b) Forging

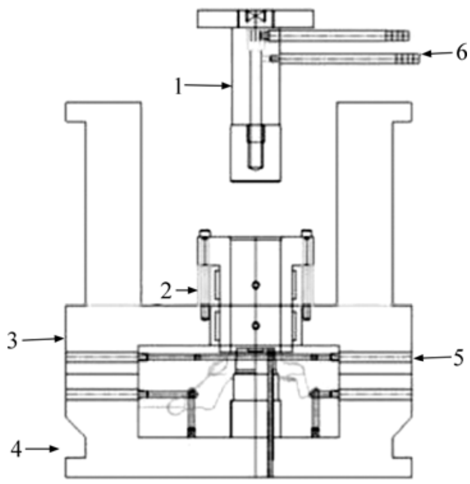

Fig.3 Schematic of indirect-type die set for rheo-forging and product: 1 Punch; 2 Sleeve; 3 Upper die; 4 Lower die; 5 Heating hole; 6 Cooling pipe

Table 1 shows the experimental conditions for rheo-forging. The vacuum pressure is fixed. Fig.4 shows the curve of solid fraction versus temperature for the A356 aluminum alloy. The curve was extracted from the MAGMAsoft program data base. The temperature was controlled for achieving the solid fraction between 30% and 50%. Solid fraction (pouring temperature) was variable in rheo-forging. Fig.5 shows the positions on the test piece subjected to observe the microstructure. The regions of each position were also studied by microscope. In order to observe the differences of the mechanical properties at different locations on the test piece, microstructure observation was carried out.

Material constitutive equation is mainly used to determine material characteristics. Semi-solid metal (SSM) process is a very complicated process of forming

Table 1 Experimental conditions of manufacture for slurry

Solid fraction/%	Vacuum pressure/kPa
30	50
40	50
50	50

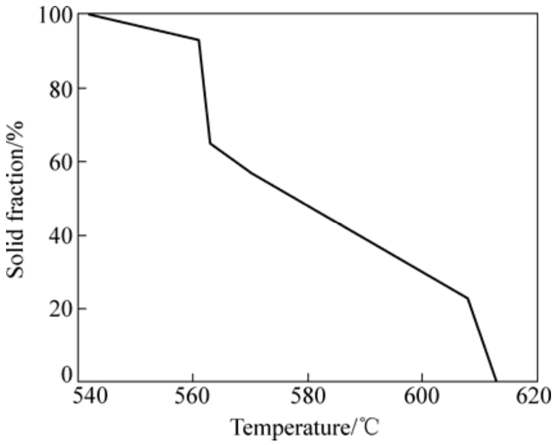

Fig.4 Curve of solid fraction vs temperature in A356 alloy

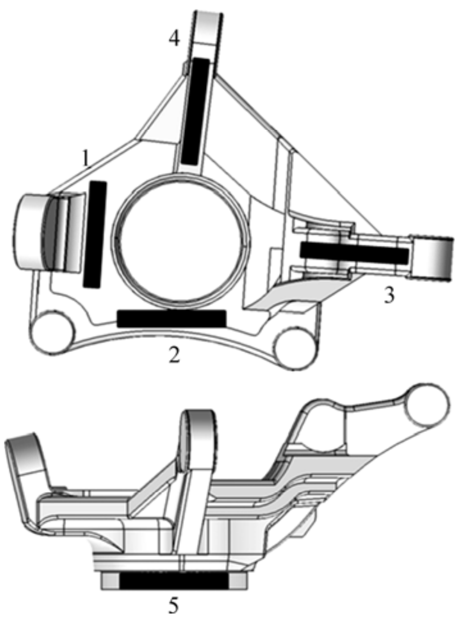

Fig.5 Positions of sample to observe microstructure

rigid viscid-plasticity material. Plastic deformation is dominant over elastic deformation, so elastic deformation can be ignored in the SSM process. Because of the sensitivity of SSM to strain rate, it is proper to take a semi-solid material as a rigid viscid-plastic material. The metal flow state of SSM is assumed to be single phase, isothermal transformation, and laminar flow for finite element method. Flow stress model can be described in the plastic forming stage as follows[6]:

$$\bar{\sigma} = f(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \tag{1}$$

where $\bar{\sigma}$ is the flow stress (yielding stress); $\bar{\varepsilon}$ is the effective plastic strain; $\dot{\bar{\varepsilon}}$ is the effective strain rate; T is the deformation temperature. The normal formula is[7]

$$\bar{\sigma} = a_0 \exp(a_1 T)\bar{\varepsilon}^{a_2}(\dot{\bar{\varepsilon}})^{a_3} \tag{2}$$

where a_0, a_1, a_2 and a_3 are constants.

The values of effective strain, effective strain rate and temperature are required for analyzing flow stress. Because of the lack of semi-solid material properties for A356 alloy in the DEFORM-3D material database, semisolid true stress–strain relationship was measured by referring to the previously conducted tensile and compression test. Stress−strain data of A356 alloy in the semi-solid state with respect to temperature was imputed into the DEFORM-3D data material database. The parameters and computation conditions that were used for the simulation are shown in Table 2.

Table 2 Process and initial conditions of simulation

Input	Symbol	Value	Unit
Material	−	A356	−
Initial billet temperature	T_b	588	°C
Initial die temperature	T_d	200	°C
Initial punch temperature	T_p	100	°C
Friction factor	k	0.2	1
Heat conductivity	H_C	0.180	kW/(m·K)
Heat transfer coefficient	H_T	35	kW/(m^2·K)
Punch velocity (constant)	v_p	20	mm/s
Mesh numbers	N	57 632	1

3 Results and discussion

Fig.6 shows the material shape with respect to stroke displacement at 580 °C with about 40% solid fraction of A356 aluminum alloy. The stress slowly increased with the stroke length increasing up to 128 mm, and then the stress rapidly increased. Upon complete closure of the die, a forging load of over 450 t was required. However, the die could not be completely closed due to the overflowing material, regardless of the forging load. The overflowing material prevented the complete closure of the die. Fig.7 shows the experimental samples fabricated by the press machine. The sample could be filled completely through the direct type forging. Experimental samples showed similar filling behavior as the simulation results.

In fact, the results of simulation and experiment showed that the direct forging process yielded poor filling cavity, as shown in Figs.6 and 7. Therefore, the indirect-type forging was used to completely fill the material in the die cavity, as shown in Fig.3.

Fig.8 shows the shape change with respect to the punch stroke. At the near end of punch displacement of

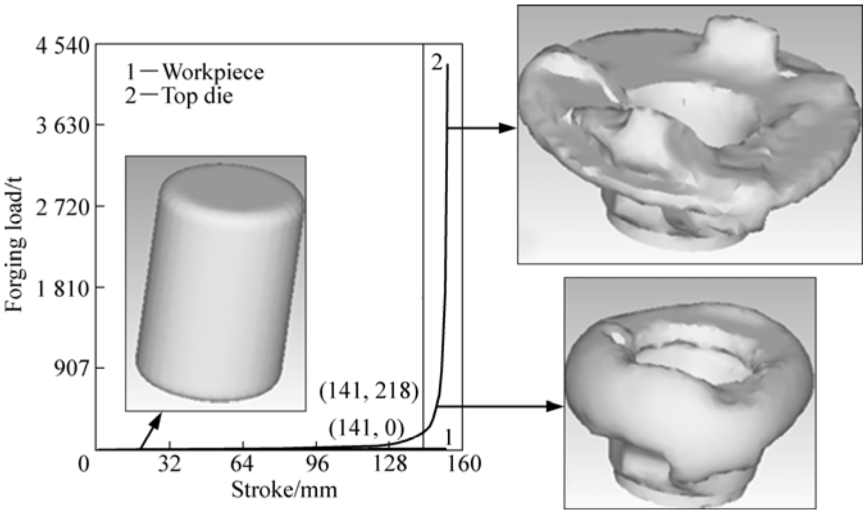

Fig.6 Simulation result of direct rheo-forging test of rheological materials

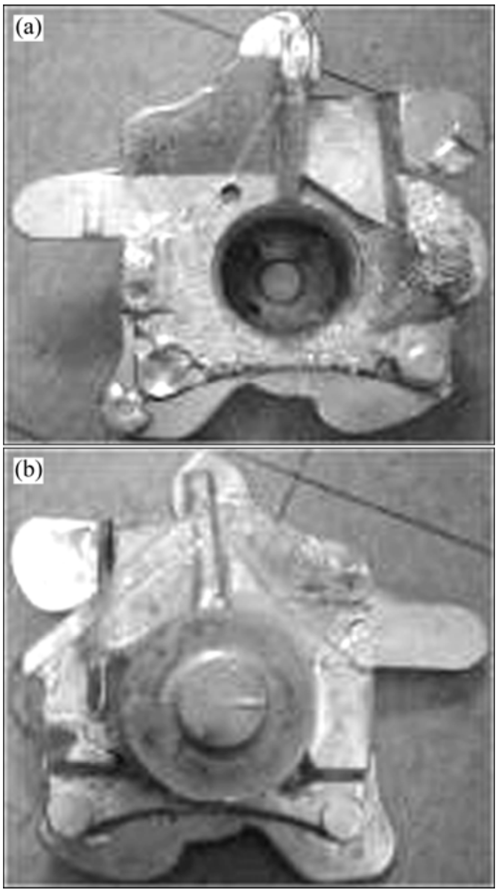

Fig.7 Result of direct rheo-forging test of rheological materials (Pouring solid fraction of 40% (588 °C))

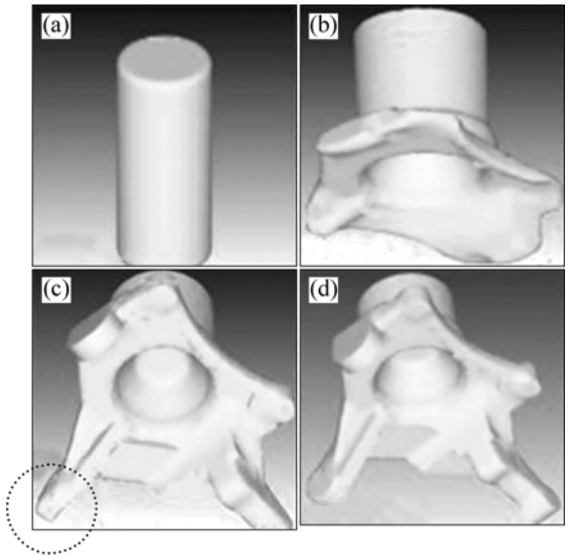

Fig.8 Shape change results with punch stroke in DEFORM 3D: (a) 0 mm; (b) 30 mm; (c) 110 mm; (d) 130 mm

about 110 mm, most of cavities were filled, except for marked region as shown Fig.8(c). When the punch displacement reached about 130 mm, all cavities were fully filled. Fig.9 shows the real samples fabricated with respect to various pouring temperatures.

All samples were completely filled above the pouring temperature of 588 °C. Real samples showed similar filling behavior as the simulation results in indirect-forging.

Material flow behavior is dependent on the temperature and the applied load. Insufficient stress and low temperature can induce non-uniform material flow, which leads to internal or surface defects. Indirect approaches such as gradient temperature and stress measurements can be used to visualize surface defects such as folding or crack.

Fig.10 shows the simulated temperature distribution and stress distribution, respectively. The branches of the knuckle had a larger temperature gradient than the other regions. Unlike the folding defects resulting from forging

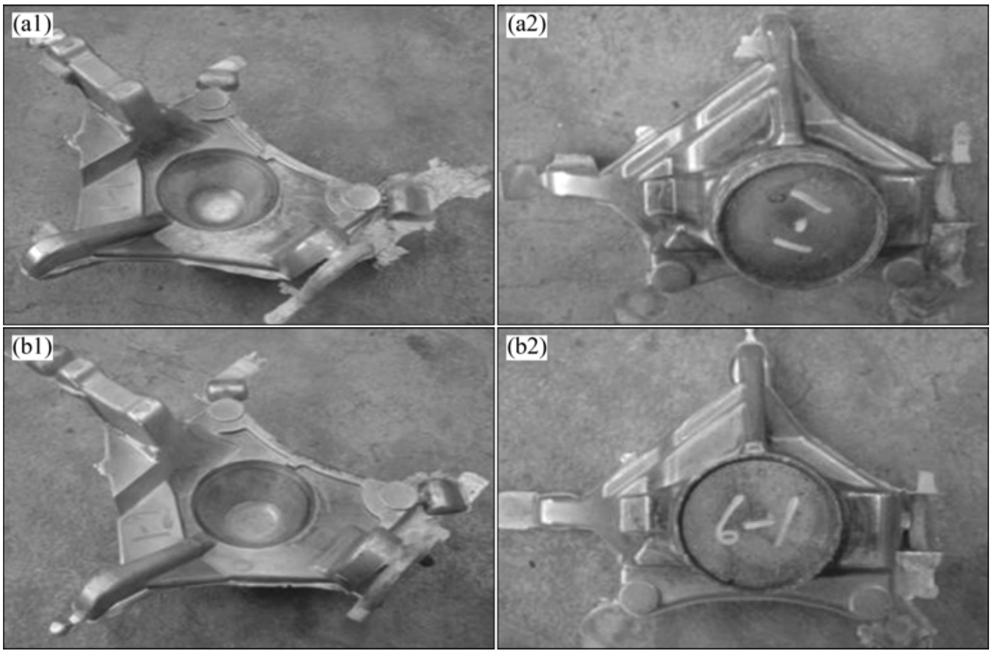

Fig.9 Result of indirect rheo-forging test of rheological materials: (a) Pouring solid fraction of 30% (600 °C); (b) Pouring solid fraction of 40% (588 °C)

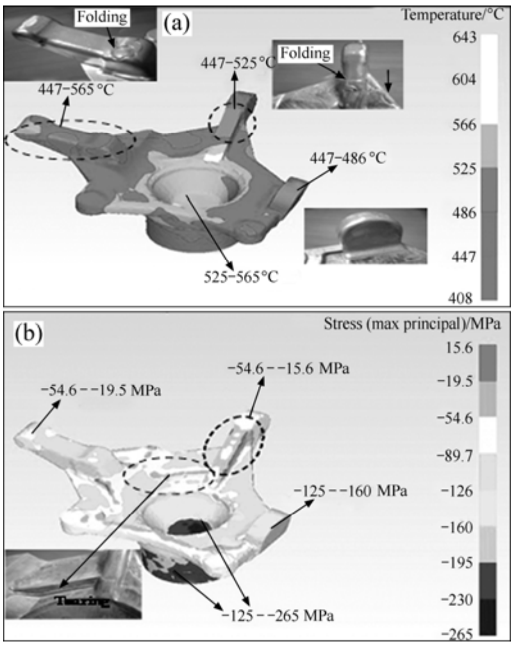

Fig.10 Prediction of defect according to temperature distribution (a) and stress distribution (b) in simulation with real sample

or casting in one phase, folding defects resulting from semi-solid forming is very often generated due to the coexistence of solid and liquid phases. Large difference of temperature is the main factor of material folding. Tearing or cracking is very often generated due to the coexistence of tensile load and compression load. Different direction loads interrupt the bonding of material during the forming process.

In semi-solid forming, liquid segregation easily occurred at high velocity due to the thixotropic characteristic. A high shear rate resulted in decreased viscosity for a given solid fraction. Material having low solid fraction flowed easily compared with already hardened material. As a result, segregation occurred in a wide region, as shown in Fig.11 (positions 1−4). On the contrary, almost primary α phase was shown at position 5. Position 5 was directly contacted by the punch. Also, material flow was slower than that of other positions. The contacted region was rapidly cooled by heat transfer. As previously stated, a material hardened by the decreasing temperature, flows less easily than materials in liquid state. The remaining liquid phase material is squeezed. It moves down to the other cavities. For this reason, liquid phase is rare at position 5.

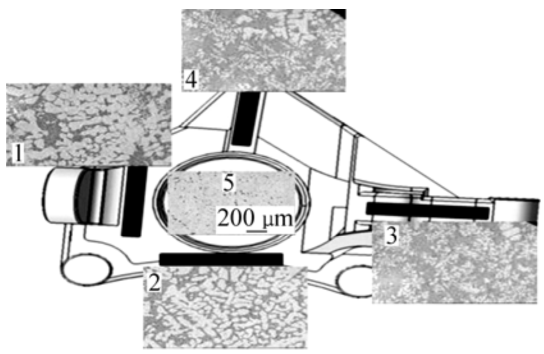

Fig.11 Microstructures of knuckle at different positions (solid fraction of 40% (588 °C))

4 Conclusions

1) In rheo-forging process, the direct forging process has poor cavity filling ability. Indirect forging can completely fill the die cavity of the material.

2) In the case of rheo-forging of a knuckle shape, the required punch load to fill the die cavity was about 200 t under 40% solid fraction (588 °C).

3) Defects such as material folding and tearing could be predicted by the process temperature and the stress distribution for an A356 aluminum alloy product.

4) In the rheo-forging process, segregations remarkably occurred at branches of the knuckle. It must be controlled to obtain uniform mechanical properties according to the changed process condition.

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