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Numerical and Experimental Study of Semi-solid A356 Aluminum Alloy in Rheo-Forging process

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Abstract

Die casting process has been used widely for complex automotive products such as the knuckle, arm and etc. Generally, a part fabricated by casting has limited strength due to manufacturing defects by origin such as the dendrite structure and segregation. 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. This paper presents the results of an A356 aluminum alloy sample, which were obtained by experiment and by simulation using DEFORM 3D. Samples of metal parts were subsequently fabricated by using hydraulic press machinery.

Key Words : Semi-solid, DEFORM 3D, Rheo-forging, Formability

1. Introduction

Rheological material forming is a near-net-shape forming process which constitutes final parts by loading the part materials at a temperature between the liquidus and the solidus [1,2]. 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 processes.

However, it is difficult to perform a numerical simulation of the rheological process because of its complicated sub processes in the phase transformation must be considered. In the rheological process, analysis based on rheological theory allows for a more exact understanding of rheo-forming products characteristic.

Rheological material has thixotropic, pseudo-plastic, and shear-thinning characteristics [3]. And, when forming rheology material, liquid segregation between the liquid and solid phases occurs, and rheological material has a complex rheological behavior [4]. Therefore, a general plastic or fluid dynamic analysis is not suitable for analyzing the behavior of a rheological material.

Therefore, the present work investigates the feasibility of applying an FEM simulation 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 equipment

2.1 Rheological billet fabrication

In this study, A356 aluminum alloy was used. Its chemical composition is given in Table 1. 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

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away from the molten metal surface [5].

Table 1 Chemical compositions (wt %) and thermal characteristics of aluminum alloys

	Zn	Mg	Cu	Fe	Si	Mn	Ti	Al	T_L	T_S
A356	0.01	0.33	0.01	0.13	7.00	0.01	0.01	Bal.	614 ℃	554 ℃

2.2 Fabrication of forging samples

Knuckles were fabricated by a press machine. The indirect-type forging process with a sleeve is needed to complete the filling of a material, as shown figure 1. Indirect-type dies consist of upper and lower die and punch. The billet is poured through the sleeve after closing the die. Then, the billet is loaded by a punch at a controlled die and punch temperature by a heating and cooling system.

The temperature conditions yield solid fractions between 30% and 50%. The variable experimental conditions for rheo-forging were solid fraction.

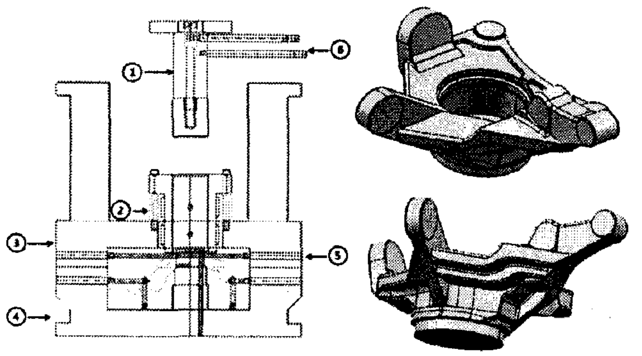


Fig.1 Schematic of dies for rheo-forging and product (① Punch, ② Sleeve, ③ Upper die, ④ Lower die, ⑤ Heating line, ⑥ Cooling line)

2.3 FEM analysis by using DEFORM-3D

Material constitutive equation is the main determinant of material characteristics. Semi-solid material (SSM) process is a very complicated process of forging of rigid viscid-plasticity material. Plastic deformation is dominant over elastic deformation in a severe plastic deformation, so elastic deformation can be ignored in the SSM process. Because of the sensitivity of SSM to strain rate, it is proper to think of 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 used rigid visco-plastic finite element method in the SSM process. Flow stress model can be described in the plastic forming stage as follows [6].

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

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

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

where a_0–a_3 are constants.

Eq. (1) is highly recommended because it can present the true material behavior. 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 in the DEFORM-3D material database, semisolid true stress–strain relationship is measured by referring to the previously conducted tensile and compression test [8]. Stress-strain data of A356 in the semi-solid state with respect to temperature was imported into the DEFORM-3D data material database. The parameters and computation conditions that were used for the simulation are shown in Table 3.

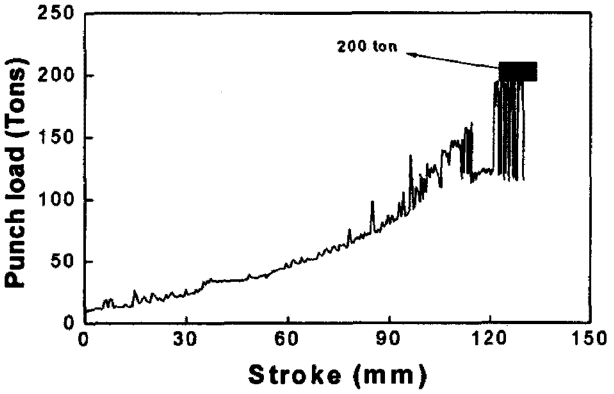
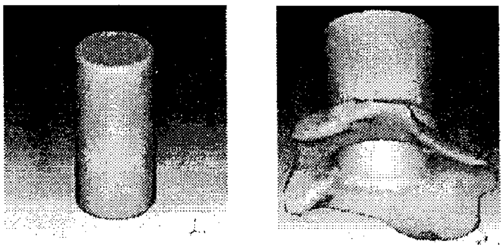


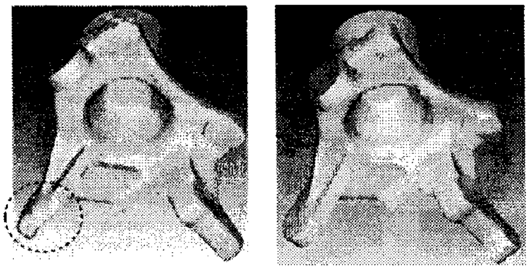
Fig.2 Stress of punch according to stroke for A356 at 588 °C (S_f = 40%) in DEFORM-3D

Table 3 Initial conditions of the simulation

Input	Symbol	Value	Unit
Material	-	A356	-
Initial Billet Temperature	T_b	588	℃
Initial Die Temperature	T_d	200	℃
Initial Punch Temperature	T_p	100	℃
Friction Factor	k	0.2	-
Heat Conductivity	H_C	0.180	kW/mK
Heat Transfer Coefficient	H_T	35	kW/m^{2}K
Punch Velocity	V_p	20	mm/sec
Mesh numbers	Mn	57632	-



(a) 0 mm (b) 80 mm



(c) 110 mm (d) 130 mm

Fig. 3 Shape change results according to punch stroke in DEFORM 3D

3. Results and discussions.

3.1 Forming load expecting according to punch stroke by simulation

Before the experiment was started, the required forging load was calculated by simulation, considering the capacity of our press machine, which was 200 Tons. As shown in figure 2, the required load was about 200 Tons at 588 °C (40% solid fraction). Figure 3 shows the shape change with respect to the punch stroke. At the near end of punch displacement of about 110mm, the cavities were almost fully filled, except for some branches as shown Fig. 3 (c). When the punch displacement reached about 130mm, all cavities were fully filled.

3.2 Surface analysis by simulation and experiment in rheo-forged sample

Figure 4 and 5 show 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 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. Therefore, an analysis of the temperature gradient is very useful for predicting a folding defect. Also, a large difference of stress brings about surface tearing or cracking, as shown Fig. 5. 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. As shown Fig. 5, tearing was generated in the low compression region or coexistence region in different load directions. Overall, real samples had similar defects as simulation samples.

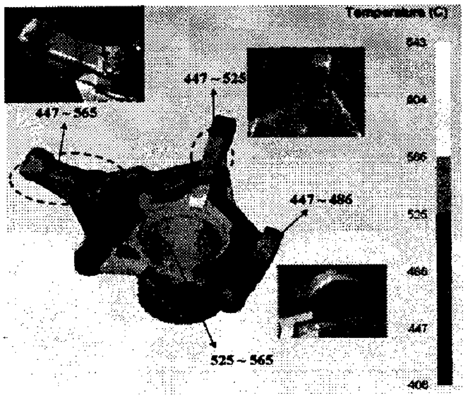


Fig.4 Prediction of folding defect according to the temperature distribution in simulation with a real sample

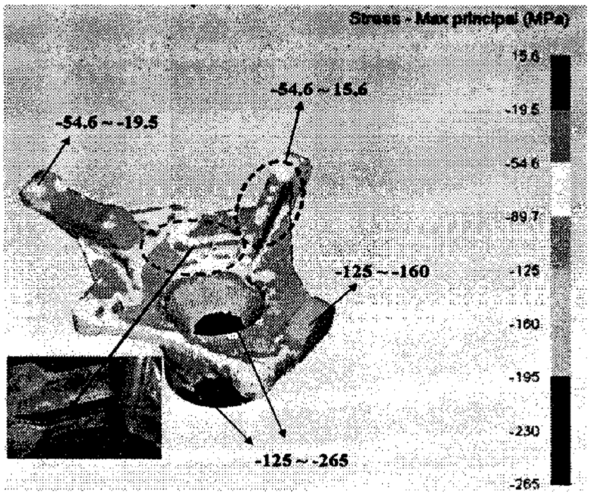


Fig.5 Expectation of crack or tearing defect by stress gradient in simulation with real sample

4. Conclusions

A rheo-forging process was simulated by DEFORM-3D and also carried out in an experiment. Rheo-forging formability of the A356 aluminum alloy in rheology state could be predicted by using DEFORM-3D . Results showed that the material behaved similary according to the pressure in the simulated and actual tests. As a result, the following conclusions were obtained.

(1) In the case of rheo-forging of a knuckle shape under about 3kg loading , the required punch load to fill the die cavity was about 200 tons under 40% solid fraction (588°C)

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

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Reference

[1] Kumar P,Martin CL, Brown S., Predicting the constitutive flow behavior of semi-solid metal alloy slurries, in M. Kiuchi (ed). *Proc. S2P-3rd,*Tokyo,(1994), 37–46.

[2] M. Sue'ry and M.C. Flemings, Effect of strain rate on deformation behavior of semi-solid dendritic alloys, *Metallurgical Transactions* Vol.13A (1982), 1809-1819.

[3] M.C. Flemings, Behavior of metal alloys in the semisolid state, *Metallurgical Transactions* Vol. 22A (1991), 957-981.

[4] D.H. Kirwood, Semisolid metal processing, *International Materials Review* Vol. 39(5)(1994), 173-189.

[5] W.S. Lee, B.J. Ye, *J. Kor. Foundrymen's Soc.* Vol.21(6)(1999), 343-349.

[6] A. Shah, E, O'Connor, D. Brabazon et al, Design of a high shear rate capillary viscometer for semi-solid metals, in Proc. S2P-8th, Cyprus, 2004

[7] H.P. Pan, Experimental research on thixoforming of semi-solid AlSi7Mg alloys, General Research Institute for Nonferrous Metals, Dissertation for the Degree of Doctor(2002), China, 77–88.

[8] S. Benke, S. Dziallach, G. Laschet, U. Prahl and W. Bleck, Modeling of the uniaxial tensile and compression behavior of semi-solid A356 alloys, *Computational Materials Science* Vol. 45(2009),633-637.