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Control of thermal contraction of aluminum alloy for precision cold forging

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ABSTRACT

Thermal contraction affects the final geometry of a cold forged product. Control of the thermal geometry changes of aluminum alloys is essential because aluminum alloys have higher thermal conductivity than other metals. Finite element analysis revealed that inhomogeneous temperature distributions cause local heat shrinkage, which lowers the accuracy of the final geometry. An optimal slide motion was proposed to ensure uniform temperature distribution. Simulation results indicated that oscillatory slide motion is superior at ensuring a uniform temperature distribution, and this was confirmed by experiments. Our study showed that process design with consideration for temperature distribution is advantageous.

1. Introduction

The cold forging process has significant advantages compared to hot or warm forging processes concerning the resulting geometrical accuracy, surface properties, and mechanical properties of the final product. However, the technique is inferior to the machining process, especially regarding product accuracy, since slight changes in workpiece dimensions occur during cold forging. The extent of geometric error depends on misalignment of upper and lower dies, the elastic deformation of tools and the specimen, stiffness of the press, and thermal expansion and contraction [1]. Therefore, it is beneficial to elucidate the factors affecting the final dimension of the cold forged product and to control them so as to raise the geometric quality of the resulting product. Numerous studies concerning process optimization of the cold forging process have been published. Lee et al. studied tool deformation in cold forging experimentally and analytically [2]. They concluded that it is important to consider suitable analytical conditions for calculation of die elastic deformation and the accuracy of final workpiece dimensions. Jun et al. proposed a combined prediction system using rigid-plastic and elastic–plastic analyses [3]. They indicated that it is possible to predict the final dimension by considering the effects of heat contraction and elastic recovery. Furthermore, the authors also published a study of geometric prediction using coupled analysis of thermal effects and elastic deformation regarding cold backward extrusion [4].

Aluminum alloys have been widely used to manufacture lightweight automotive bodies and parts. Although aluminum alloys are inferior than steel from the point of view of material cost, they exhibit nearly equivalent specific rigidity and about twofold specific strength compared to steel. To compensate for the greater material cost, it is considered imperative that process conditions be optimized to reduce waste material. To this end, Jensrud et al. proposed a new thermomechanical process for aluminum forging [5]. They showed that it is possible to reduce the load without reduction of the hardness under the proposed optimum processing conditions. Khaleed et al. performed three-dimensional analysis including thermal effects for a flash-less cold forging product of aluminum alloy [6]. They obtained a good agreement with experimental results and optimized the initial shape of the workpiece.

Thus, geometry prediction of cold forging and process optimization of aluminum forging have been reported. However, few studies evaluate process design in the absence of geometrical optimization of the workpiece and die for precision cold forging of aluminum. The authors have attempted to increase the accuracy of the final dimension of backward extruded steel using a servo press with several slide motion [7]. The influence of thermal contraction on the final dimension was investigated in the case of several servo press motions, but the optimum process conditions and theoretical considerations have not been evaluated. Therefore, in this research, simulations and experiments were carried out to improve dimensional accuracy by controlling thermal contraction and elastic recovery of the workpiece in the aluminum cold forging process.

2. Experimental procedure

2.1. Proposal of optimum slide motion

The authors have investigated the influence of slide motion using a servo press on the final dimensions of a workpiece for the steel backward extrusion process [7]. The authors found that the temperature distribution present immediately after the ejection stage more strongly affects the final dimensions than does elastic recovery. Note that this temperature distribution is generated in the deformation stage. In the case of conventional crank press motion, the temperature distribution is inhomogeneous because high temperature is distributed locally around the punch edge. This local distribution is retained during the unloading, punch removal, and ejection stages. As a result, local heat contraction

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occurs. These results suggest that motions that can promote workpiece cooling in the container and that cause the workpiece to cool during the deformation stage are suitable to enforce a homogeneous temperature distribution. Thus, three types of slide motions, shown in Fig. 1, were selected. Motion A represents the motion for a conventional crank press. The movements associated with Motion B and Motion C represent cooling in the container and cooling during the deformation stage, respectively.

2.2. Experimental conditions

An Al–Mg–Si alloy A6061/JIS material was used as a specimen. The initial and final shapes of the specimen are shown in Fig. 2. The reduction of area is 49%. Billets were treated with aluminum fluoride and a soap coating as a lubricant. The SDE1522-SF (AMADA, Japan) servo press, with a 1500 kN maximum load capacity, was used as the experimental apparatus. The press forming speed was equivalent to 50 spm. For Motion B, the punch was kept at the bottom dead point for 1.62 s. In the case of Motion C, the amounts of return b1 and forward b2 were 0.5 and 0.7 mm, respectively. The total process time for both Motions B and C was 3 s. A schematic of the die design is shown in Fig. 3. The punch was made from cemented carbide and the die was made from high speed steel SKH51/JIS. A hard TiCN coating was applied on the punch surface by physical vapor deposition. A guide sleeve was used for aligning the die and the punch.

2.3. Evaluation method

Variation of the outer diameter was measured to evaluate the dimensional accuracy of the backward extrusion process using a Crysta-Apex C7106 (Mitutoyo, Japan) CNC coordinate measuring device. The experiment was conducted repeatedly two times under same experimental condition. The outer diameter was measured at 2 mm intervals for a total of 360 measuring points at each height. Repeated results showed almost the same values, thus the average value of the total 720 measured points at each height was plotted to describe the outer profile of the specimen's geometry.

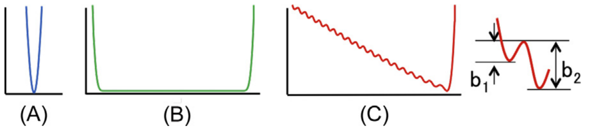

Fig. 1. Schema of slide motions: (a) Motion A, (b) Motion B, (c) Motion C.

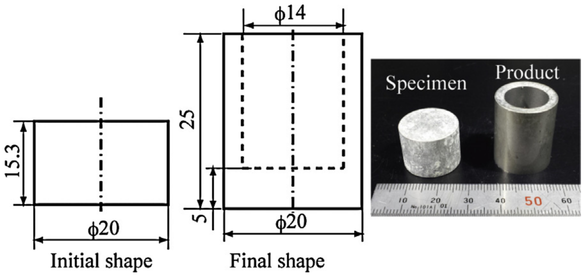

Fig. 2. Initial and final shape of the workpiece.

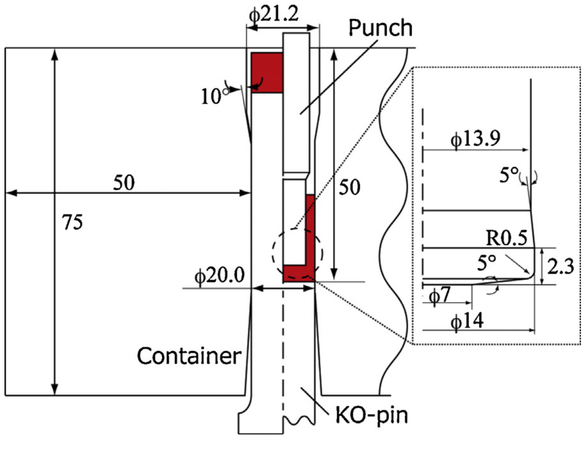

Fig. 3. Tool geometry in the backward extrusion process.

3. Experimental result

The final outer profiles are shown in Fig. 4. Ideally, the final outer shape should agree with the inner diameter of the container (=20.00 mm); however, as seen from the figure, the outer diameter differed from the inner diameter in all the three cases. It is presumed that these errors were caused by the elastic deformation of die and billet, and by heat constriction. However, the shape extruded by Motion C showed a comparatively straight profile. In the case of Motions A and B, the outer profile was a concave line. If the products can be manufactured with a straight shape, it is only necessary to adjust the inner diameter with consideration for error. Thus, it is deemed that Motion C is the appropriate condition for precision forming in case of the backward extrusion process. As proposed in Section 2, it is presumed that this result was obtained because of a homogeneous temperature distribution caused by the oscillatory motion during deformation. In contrast, although it seems that Motion B has a homogeneous temperature distribution because the billet is kept in the container after deformation, local deformation was observed similar to the case of Motion A. Therefore, thermal coupled elastic–plastic finite element analysis was performed to elucidate the deformation behavior during the backward extrusion process.

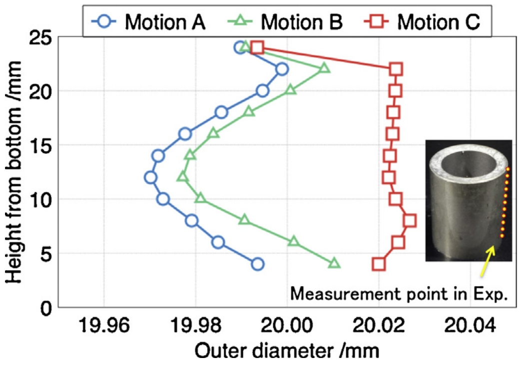

Fig. 4. Experimental results for the three slide motions considered.

4. Analytical condition

Commercial software Simufact.forming Ver. 11.0 was used to perform the simulations. The simulation conditions used are shown in Table 1. Flow stress of the billet was extrapolated by Hollomon's equation, which was obtained from a cylindrical compression test. Material properties, except for the flow stress of the aluminum alloy, were obtained from the simulation software database. The ring upsetting friction experiment was conducted to identify frictional coefficient using phosphate-coated specimen.

Table 1
Analytical conditions.

Material property	Workpiece	Punch	Container
Flow stress (MPa)	$\sigma = 376 \cdot \varepsilon^{0.012}$	–	–
Yield stress (MPa)	365	–	–
Young's modulus (GPa)	69	600	210
Poisson ration	0.3	0.3	0.3
Heat conductivity (J (ms K)$^{-1}$)	193	70	20.6
Specific head (J (kg K)$^{-1}$)	880	293	439
Heat expansion coefficient (K^{-1})	3.00×10^{-5}	5.30×10^{-6}	1.19×10^{-5}
Boundary condition			
Friction coefficient		0.1 (Coulomb's law)	
Heat transfer coefficient (W m^2 K^{-1})		500 (between air) 30,000 (between WP and tool)	