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Contact stress and temperature during air-stamp hammer upsetting of a circular cylinder

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ABSTRACT

Air-stamp hammer forging is a traditional hot-forging method. This method is mostly used based on the operator's skill and not on the measurement of the contact stress condition. In this study, we measured the contact pressure and friction on the tool surface during the upsetting of a circular cylinder of hot steel using an air-stamp hammer. For the upsetting process, we installed friction sensors that could detect the pressure and friction stress on the tool surface on the flat die. A tool surface temperature sensor with a thin thermocouple was also installed 0.3 mm under the tool surface. During the upsetting process, the pressure near the center increased with the increase in the ratio between the diameter and the height. The friction was higher at greater distances from the center than it was near the center. We investigated the relationship between the pressure and friction distributions at the end of the stamping when the material had a high diameter-to-height ratio; this relationship was compared using elemental analysis. The results show that the contact-stress behavior observed during hot forging was similar to that observed in cold forging without a lubricant. The tool surface temperature rapidly increased during stamping but also increased when the tool surface had barely touched the workpiece. The data obtained about the pressure and friction behavior will be useful for designing new forging processes, and the information about the effects of stress and temperature on the tool surface will be useful for investigating tool wear.

1. Introduction

Stamp-hammer forging is one of the primary methods of hot metal forming that applies a high-impact force using a dropping hammer. It has a long history of more than 200 years, but the phenomena related to this process, such as the contact stress and temperature on the boundary surface during the forging, are still not well understood. This may be because of the absence of a sensor that detects the contact stress at the impact time of the stamp hammer. In later years, the hydraulic press and mechanical press were developed, and these techniques have been experimentally investigated. The drop-hammer forging process involves repeated stamping of a material using the same die to obtain the final shape. Each hammer-dropping height and stamping cycle depends on the operator's skill. Stamp-hammer forging is still widely used because drop-hammer forging has an advantage that only one die set is used repeatedly for stamping the material into its final shape. In addition, the forging machine is simple and compact because it uses the potential energy of the hammer assisted by air pressure. The fundamental science behind drop-hammer forging is still unclear because the method depends on the operators' skills.

A number of studies have been conducted on the various forging methods. Johnson and Nasmyth [1] described the origin and history of the steam hammer. Huang et al. [2] studied the intelligent classification of the drop-hammer forging process. Xuewen et al. [3] developed a knowledge-based design system for hammer forging. These approaches are based on skills and knowledge and not on the actual measurement of physical parameters.

To understand the forging process better, we need to study the design of the deformation process and also the tool wear or the tool fracture mechanism using impact stress. To study these aspects of the forging process, we need to determine the forging load, the contact stress, and the tool contact temperature. The contact stress and temperature affect the metal deformation, the forging load, and the tool wear. Measurement of the boundary stress and temperature in the metal forming process plays an important role not only in elucidating the forging phenomena but also in improving the tool design and computer simulations. However, it is difficult to directly measure the contact pressure and friction on the tool surface during the plastic-deformation processes.

There have been many attempts to develop boundary stress sensors

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for metal forming processes. Siebel and Lueg [4] first developed the pressure-pin technique in which a detecting pin was embedded in the tool surface. MacGregor and Palme [5] measured the distribution of contact pressure in the rolling of metals. Van Rooyen and Bachofen [6] applied the pressure-pin technique to detect the frictional stress in cold rolling, as in the oblique pin mechanism. Yoneyama and Hatamura [7] developed a stress sensor that could detect both the pressure and the frictional stress in any direction by using a single detecting pin with a three-directional force-detecting structure. Yoneyama [8] provided several examples for measuring the pressure and frictional stress in the forging process using this sensor. Jeswiet and Nyahumwa [9] also developed a sensor that could detect both the pressure and the frictional stress. Nyahumwa [10] applied this technique to detect the frictional forces during cold rolling. However, these pressure-pin techniques leave a gap between the detection pin and the surrounding hole in the tool, and the deformed material may flow into this gap. In addition, it is difficult to keep the sensor and tool surfaces at the same level during the process; this influences the friction condition.

To eliminate the gap and level difference in the measurement of contact stress, Yoneyama et al. [11] developed a pressure sensor using an optical fiber displacement meter. Yoneyama [12] also developed a pressure sensor using strain gauges with a structure comprising an inner shaft and outer tube connected at the tool surface and joined by a thin plate at the both ends. Dellah et al. [13] developed an embedded strain-gauged diaphragm sensor press-fit into the tool surface. Lupoi and Osman [14] developed an under-surface pressure sensing technique, which was explored using the pressure-pin technique. Jeswiet et al. [15] proposed a sealed cantilever pin for the measurement of friction in a rolling process. Yoneyama and Takahashi [16] proposed a principle structure to detect the pressure and friction without any gap and without any level difference on the tool surface; this structure was used to detect the pressure and friction on the container surface in an aluminum hot extrusion. Yoneyama [17] designed a friction sensor for hot-metal forging applications. In this paper, we have used the measurements obtained from this friction-sensor stamp-hammer forging.

The upsetting process is a basic plastic-deformation process used to form a proper shape for subsequent forging steps. It is also a convenient process for investigating the friction conditions in metal forming. Kojima and Mizuno [18] measured the contact pressure distributions in the upsetting of cylindrical billets by measuring the elastic strain distribution in the loading platen. Wang [19] proposed the evaluation of friction from the velocity field in dynamic plane upsetting. Hu et al. [20] measured the pressure distribution on the die surface during the upsetting by using multiple pressure pins. Li et al. [21] showed that the instantaneous friction coefficient increases with the true strain during the hot compression of a cylindrical sample; this study was based on finite element analysis (FEA) and a comparison between the various shape changes in the experiment. Tan [22] proposed a dynamic friction model in which the friction depended on both the time rate of strain and the normal pressure and applied this model to the cylinder upsetting process.

This study has two main purposes. The first purpose is to use friction sensors to elucidate the fundamental roles of contact stress, tool surface temperature, and forging load in the stamp-hammer upsetting process. Our second purpose is to investigate the relationship between the contact pressure and friction during the upsetting of a circular cylinder during hammer stamping. The results can be used in future studies to improve the method used for the stamping process and for the tool-wear analysis in stamp-hammer forging.

2. Experiment

2.1. Experimental setup

The experimental setup for the upsetting of a hot steel circular cylinder is shown in Fig. 1. The air-stamp hammer used in this study was a DIE- MAX 150 made by the Otani Machinery Mfg. Co., Ltd. The mass of the dropping hammer including the die mass was 2500 kg. The maximal stroke was 1150 mm. In the lower flat die, an insert block was installed with pressure, friction, and temperature sensors. The outputs of these sensors were transmitted to a data recording system beside the hammer press. A high-resolution infrared thermal-imaging camera R300SR-H (made by Nippon avionics Co. Ltd.) was set approximately 3 m behind the hammer to detect the changes in the surface temperature of the workpiece. The measurement accuracy was 2 °C, and the spatial resolution was 1.21 mrad. Therefore, one pixel of the camera image was approximately 3.6 mm^2 at the distance of 3 m; this resolution was enough for the workpiece of diameter ranging from 60 mm to 120 mm. A high-speed camera was also located approximately 3 m behind the hammer to capture the ram motion. A regular video camera was used to record the upsetting motion from the front.

The structure of the flat lower die is shown in Fig. 2. An insert block made of alloy tool steel for hot forging (SKT4) having a diameter of 200 mm and a height of 120 mm was installed in the 500-mm square lower die. Contact-stress sensors were embedded at locations 10, 35, and 60 mm from the center of the insert block. A temperature sensor was installed at 30 mm from the center. To detect the stamping load, strain gauges were fitted on the side groove surface of the insert block. Therefore, the insert block also became a sensor for detecting the stamping load. We machined and finished the top surface of the insert block by using a lathe. The surface roughness was approximately Ra 1.6.

In Fig. 3, we present the structure of the contact-stress sensor. Fig. 3 (a) shows the cross section of the sensor block. The area that detects the pressure and friction is approximately 5 mm in diameter on the block surface. Fig. 3(b) shows the machined sensor block made of SKD61 tool steel alloy. Two strain gauges (KFH-02-120-C11-11H4M3, Kyowa Electric Company) were fitted to the detection surface of the sensor block, as shown in Fig. 3(c). The temperature resistance of the strain gauge was 250 °C, which was quite high. Commercial strain gauges having higher temperature resistances were not able to fit into the small sensor. The temperature increase on the tool surface was instant. Even when the surface temperature increased more than 250 °C, the increase of the temperatures of the strain gauges located 6 mm under the tool surface was low at least during the instant upsetting time.

Fig. 4 illustrates the deformation principle for detecting the pressure and friction by using the sensor. The thin plate is connected by two beams, which are also connected to the tool surface part; the plate deforms when subject to pressure (see Fig. 4(a)) and friction (see Fig. 4(b)). The pressure is determined as the sum of the two strains, whereas the friction is determined as the difference between the two strains. The sensor design and calibration method are described in detail in [17]. The output performance for pressure was examined by applying the load to the top surface of the sensor pin. The output coefficients were also checked by comparing the detected pressure and the mean pressure that was obtained by dividing the load by the contact area in the initial stage of the upsetting of a circular cylinder. The ratio between the diameter and the height was not high, and we expected almost flat pressure distribution on the contact surface. The output performance for friction was examined by applying a tangential force under compression to a small circular aluminum cylindrical block on the sensor top surface. We calculated the pressures p_1, p_2, and p_3 and the frictions f_1, f_2, and f_3 at each of the sensors using the strain gauge outputs ε_1 and ε_2 as follows:

$$p_1 = 0.743(\varepsilon_1 + \varepsilon_2),\ \ p_2 = 0.585(\varepsilon_1 + \varepsilon_2),\ \ p_3 = 0.51(\varepsilon_1 + \varepsilon_2) \tag{1}$$

$$f_1 = 0.93(\varepsilon_1 - \varepsilon_2),\ f_2 = 1.25(\varepsilon_1 - \varepsilon_2),\ f_3 = \varepsilon_1 - \varepsilon_2 \tag{2}$$

In these equations, the unit of the pressure is MPa, and the unit of friction is also MPa. The value of the strain output is 10^{-6}.

As shown in Fig. 5, we embedded a temperature sensor with a thin-sheath thermocouple of 0.25 mm diameter made by Okazaki