Experimental Analysis on Behaviour of Adhesive Scale in Hot Die Forging to Improve Surface Quality of Automobile Parts

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Deep dent defects on the automobile parts produced by hot die forging have become problems because the dents were disadvantageous to the strength of these parts. The dents may have been probably caused by scales of hot billets. The behaviour of these thick scales in hot die forging was experimentally analyzed in this paper. The dents gradually grew bigger and changed the shapes every forging shot before the scales periodically transferred to the workpiece. The deep dent defects frequently formed at the part of the workpiece with large plastic deformation. Additionally, it was found the scales consisted of the oxide/non-oxide layers derived from the hot billet materials by microscope observation and electron probe micro analysis. It was estimated that the thicker scales were formed by layered pick-up and adhesion under severe tribological conditions. Adjusting preform shape and controlling lubrication were proposed to decrease the defects.

Keywords: tribology, forging, adhesion, plastic deformation

1. Introduction

The weight reduction of an automobile considerably contributes to the improvement of fuel consumption and to the reduction of emission. To weight reduction, material innovation [1], light weight metals, and high strength steel are applied. These materials are selected in chassis parts such as suspension arms and in engine parts also. In these parts, sharp shapes and deep impressions are preferably designed to increase in their rigidity [2].

These large and strong parts are often manufactured by hot forging, because the material flow stress decreases and the large deformation is possible at a high temperature, but the die for hot forging is likely to be damaged by wear and the surface quality of work deteriorates by thick oxide [3]. Thus, the cooling conditions of the dies were investigated precisely [4], and frictional coefficients in hot stamping were evaluated [5-7]. Surface quality improvement is a key of contribution to the weight reduction of automobile by hot forging. Moreover, reducing environmental emission from lubrication processes for metal forming is also required [8]. Thus, in hot rolling and hot stamping a lot of good research works have given very useful information[9-15]. In hot forging, however, there were not many research works on tribology. The thick oxide scale may practically make a crucial damage on hot forged products. This problem has never been solved for a long time in hot forging. Recently, a better surface quality has been strongly needed for precision forging in also hot forging. In this paper, the behaviour of adhesive scales and dent defects is experimentally analyzed in a test that is nearly practical hot die forging to improve surface quality in automobile parts produced by hot forging.

2. Forging test and conditions

2.1. Nearly practical forging test

To evaluate the surface quality of forged works, a nearly practical hot forging test is carried out. The test was designed by referring a closed-die forging as shown in Fig. 1. Three stages and multipart dies are used in the multiple forging. At the first stage, a simple bar billet is forged to be deformed into the first preform. The temperature of this preform is still high. The material flowing of the preform is largest in these stages of forging. At the second stage, the shape of the second preform becomes shaper. At the third stage, coining is applied to the finish work which is thinned down and its impression becomes deeper.

These forging conditions are severe in tribology. Large material flowing and high temperature cause
heavy wear at the first stage. This multipart die developed to improve product efficiency, because the single bar is divided in two parts for one shot. However, the material flow is large and the tribological condition is severe.

By referring to this forging, a nearly practical forging test as shown in Fig. 2 is carried out. A billet is covered with graphite coating to inhibit excessive oxidation. It is heated up to 1000°C in the high-frequency induction furnace. To measure the thickness of the primary oxide of the billet, the work is cut after cooling it. The cross section of this work is shown in Fig. 2. The oxide thickness is about 20 μm. It contains a large amount of FeO and a small amount of Fe₂O₃ and Fe₃O₄. The disadvantageous dents having about 200 μm depth cannot be directly formed by this thin oxide scale.

This forging test is included in close-die forging with flash and it is conducted at single stage from the bar to work. The early 400 works are investigated in detail.

Finally, the used die is cut to observe after 3500 shots.

2.2. Test conditions
Table 1 shows the chemical components of the testing billet and die. The billet material is manganese steel containing a large amount of Mn and carbon. The die material is hot die steel containing a large amount of Cr, Mo, V but little amount of Mn. The testing conditions are summarized in Table 2. The billet is a round bar. This is covered with graphite coating to inhibit oxidation after it is preheated at 200°C. After the graphite coating is dried, the billet is heated up to 1000°C.

The die is quenched and tempered and it is surface-treated by iron nitriding. The substrate of the die has a hardness of 500 HV. The nitriding layer has a thickness of about 100 μm and the surface has a hardness of 1050 HV. The die is heated at about 250°C before it is sprayed with a water based-non graphite lubricant. The die temperature is not controlled during the forging test. A mechanical press having a loading capacity of 30 MN and 20 strokes per minute is used. This series of forging test is automatically operated using transfer machine.

2.3. Surface deformation of work
A special billet having 10 mm × 10 mm grids is also applied to estimate the material flow on the work surface in the forging test. The grids are grooved on the cylindrical surface by machining. A groove has a width of 1 mm and a depth of 0.5 mm. A pitch between the first groove and the second one is 10 mm. These grooves are filled with copper by plating.

The visible flowing grids appear as shown in Fig. 3 when the copper lines are rinsed with concentrated nitric acid after forging. Figure 3(a) shows the considerably larger metal flow near a small end of the beam. In Fig. 3(b) the numbers means the length of line between a pair of grids. The longest line is three times as long as the initial line. Additionally, a large share deformation occurs between a small end and a beam.

![Fig. 1 Reference stages of die forging processes using multipart die](image1)

![Fig. 2 Procedure of forging test using multipart die and section of work to measure thickness of primary scale](image2)

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Table 1 Materials of billet and die

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
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<tbody>
<tr>
<td>Billet</td>
<td>0.38</td>
<td>0.25</td>
<td>1.50</td>
<td>&lt;0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die</td>
<td>0.40</td>
<td>1.0</td>
<td>&lt;0.50</td>
<td>5.0</td>
<td>1.30</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 2 Conditions of forging test

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Billet size</td>
<td>200 mm in length and 34 mm in diameter</td>
</tr>
<tr>
<td>Billet temperature</td>
<td>1000°C</td>
</tr>
<tr>
<td>Billet Pre-coating</td>
<td>Graphite type lubricant for hot forging</td>
</tr>
<tr>
<td>Die Lubrication</td>
<td>Water-based-non graphite type containing mainly 18% Na-isophthalic acid</td>
</tr>
<tr>
<td>Nitriding of die</td>
<td>Iron nitriding, 100 μm in thickness, hardness 1050HV, (die substrate: 500HV)</td>
</tr>
<tr>
<td>Press</td>
<td>Mechanical knuckle press, 20 spm, 30 MN</td>
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After 3500 shots, many cracks and heavy wear generated on the severe deformation part which increases in the surface extension by three times.

3. Results and discussion

3.1. Investigation of dent defects

An example of a large dent on a work surface near the small end of the beam is shown in Fig. 4. This work surface is seemed smooth after forging as shown Fig. 4(a). However, when the large scale is removed by pricking the work surface using sharp pin, the large dent appears on the work surface as shown in Fig. 4(b). In a practical forging process, the works are shot-blasted to remove the oxide sales and to add the compressive residual stress on the work surface in the subsequence operation. The dent defects are often found during this operation of shot-blasting. A deep dent with a depth of 200 μm decreases the fatigue strength of the work. Especially, this is a serious problem in a precise part made of a lightweight material.

Instead of shot blasting, the early 90 works were pricked with a pin to investigate the dent defects. Fig. 5 is a map that shows where dents appear and how many dents appear. Many dents are found near the small end of the work. Thus, this area where the dents often occur is equal to an area where large deformation occurs. The large dent defects periodically occurs at about 10-shot intervals. Fig. 6 shows an example that the shape of dents change with consecutive shots from No. 61 to No. 65 near the small end of the beam. The shape change is related with the previous shape. This means that the scale remains on the die as its shape changes at some consecutive shots.

The primary oxide has a thickness of about 20 μm and has a main component of FeO. It is known this oxide can deform plastically in hot rolling [9,10,13,14,16,17]. Probably, similar phenomenon occurred in this hot
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forging test. The scales consisting of the primary oxide can elongate with thinning when the hot work is plastically deformed. However, thick scales filling the dents were 200 \( \mu \)m thicker. Additionally, it is known the oxide scale can adhere to the tool or the work [10,15]. Thus, these scales can grow 200 \( \mu \)m thicker if they adhere to the die and pile up on the die.

3.2. Observation and analysis of section of scales

To understand the mechanism of forming the thick scales, the behaviour of the oxide scales on both work and die is observed and analyzed in this test modelling nearly practical hot forging. The work covered with resin is cut near the small end of the beam. The cross section is polished, and it is etched with Knightal reagent. The cross-sectional view is observed in Fig. 7(a). The adhesive scale filling up the dent is thicker than 100 \( \mu \)m. It is much thicker than primary oxide with thickness of 20 \( \mu \)m. There are a small number of cracks in the scale. It means the FeO is ductile and deformable at about 1000°C [8,9]. By careful observation, there are etched layers of non-oxide work materials. They are imperfect layers because it may be sheared strongly.

The results of EPMA analysis is shown in Fig. 7(b). Non-oxide particles exist in the thick scale. These non-oxide particles also contain a large amount of Fe and Mn. They are elements of the work material. Therefore, the non-oxide particles are derived from the work. The X-ray intensity is not uniform and it indicates layers with vague flowing patterns.

The die is cut for observation and analysis after 3500 shots. The cut specimen is polished and etched. Figure 8 shows the section of the die near the small end of beam. This die surface is extremely damaged. The deep cracks progress here. The nitriding layer is partially removed. The surface of the die is also plastically deformed. These suggest considerably severe conditions. By more detail observation, at the entrance of the crack, a scale with some layers is found. The results of EPMA analysis show traces of the thin layers derived from work. It contains a large amount of Mn. In the scale, very thin layers containing rich Cr also exist. The grown thick scales consist of oxide layers of work, non-oxide layers of work, and very thin layers of die material. It is estimated that the scale grow on the die with piling up [18]. The scale is plastically deformable and it is likely to adhere to die and work.

From these results, we judged that prevention of sticking adhesive scale is a key to prevent large dent defects. The large dent defects remarkably decreased when adjusting the shape of the preform and lubrication controlling [19] were proposed. For example, the shape of the first preform is changed to reduce the large plastic deformation by adding intermediate shape between the bar and the first preform. As regards the lubrication technique, the die temperature and a spraying quantity of lubricants should be more precisely controlled. Especially a suitable temperature of the die must be found and be kept for the non-graphite lubricant [19]. Thus, the better-lubricated conditions are improved to reduce adhesion of the oxide scales and the raw material of the work.
4. Conclusions

Nearly practical hot forging test was carried out to investigate the formation of the dent defects and thick adhesive scales. Although the dents may have been probably caused by scales of hot billets, the primary oxide scale is too thin to form the deep dents. By the observations of the periodically changing shape of the dents at the consecutive forging shots, it was shown that the scales were growing bigger and thicker before these scales dented the work surface. Additionally, by the micro observations and electron probe micro analysis, it was found the scales consisted of the several oxide and non-oxide layers of the work materials. It was estimated that the thicker scales were formed by layered pick-up and adhesion under severe tribological conditions. From these results, to decrease the dent defects in hot die forging important measures were proposed as follows: 1) adjusting preform shape to reduce sliding length between the die and the work at the first stage for making a rough block, 2) controlling appropriate die temperature and quantity of a lubricant to apply the sufficient lubricants to the whole impression of the forging dies.

References


