Study of the Hardening in Middle Shaft During Cold Forging

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Abstract. Cold forging is a common processing method. It is fast, precise, and produces high strength. The purpose of this study was to process products by using a cold-forging technique. This study is aimed at achieving hardness of a certain standard without using heat treatment; computer-aided engineering (CAE) analyses were conducted with different diameter settings but the same methods and molds. Tests were conducted to understand the influence of the changes in material diameters on their material hardness values. We expected to produce workpieces of a specific hardness at the lowest cost. An actual cold forging case was conducted. First, Deform-3D (finite element analysis software) was utilized to conduct a computer-aided engineering forging analysis. How the internal stress distribution and equipment output tonnage changed as the diameter of the material changed was observed and compared against the actual hardness. This study discovered that the location where large elastic deformation occurred (i.e., where the stress concentration occurred), the hardness of the cold forging piece at that location increased. The simulation and experiment results revealed that a large area reduction rate of the intermediate shaft formation resulted in dense forging streamlines, high hardness, and substantial hardening effects.

1. Introduction

Metal forming processes using forging and extrusion comprise cold forging, warm forging, and hot forging. Cold forging is processing without heating. In other words, it increases the hardness and toughness in a ductile metal through elastic deformation and dislocation [1-2]. Hot forging is primarily used in processing large mechanical parts and materials with a large work-hardening coefficient. The forging temperature must be maintained at a temperature identical to or higher than the recrystallization temperature of a material. Compared with cold forging, hot forging increases a metal’s plasticity and reduces forging stress. However, hot forging easily produces oxide layers, and relevant sizes cannot be easily controlled [3]. Warm forging is an improved method comprising the strengths of both hot and cold forging. Although materials are heated using this method, they do not reach a metallographic state. Moreover, their load is smaller than that from cold forging, scales do not develop from high-temperature oxidation, and their processing size can be controlled [4-6].

Cold forging enhances the mechanical characteristics of materials, so it is commonly utilized in the auto parts manufacturing industry; and warheads, rockets, weapons, and military equipment parts for aerospace industry, and the defense industry. Although forging increases material hardness, to reach a certain hardness, heat treatment must be adopted to alter the internal structure of a material. To increase surface hardness, the surface structure must be altered through methods such as surface
blasting or polishing. Although the aforementioned techniques are commonly used to increase material hardness, these post-forging treatments for hardness result in additional time and production costs. Therefore, this study used a real case to verify methods not involving post-forging treatments to increase material hardness. The forged object in this study was an intermediate shaft found in cars with electric power steering (EPS). Deform-3D was used to analyze the locations of stress concentration [7], the machine output tonnage, and the hardness of the workpiece forged in this study under different diameters to evaluate whether the acquired hardness met the target value.

2. Literature Review
In 2002, Janicek et al. [8] used workpieces of various diameters and bolts of the same size as the workpieces to process materials without heat treatment and observe the hardness range. Shi and Yi [9] stated that when materials are under plastic deformation, under a local plastic deformation condition, the material organization and stress relocation can be utilized to reduce stress concentration, whereas under ununiformed plastic deformation, a balance can be reached through work hardening and mechanical experiments. Due to plastic deformation caused by the molding process, the hardness of a workpiece formed through cold forging increases, and the hardness influences the mechanical properties of the workpiece. In the present study, a method was developed to optimize the shape of materials and molds to reduce changes in the hardness distribution. The proposed method was suitable for backward extrusion. A finite element analysis (FEA) model that described the material mechanics behavior during the processing was developed to predict the effective strain distribution in the workpiece. The correlation between the effective strain and hardness was analyzed to determine the hardness distribution [10-11]. Tumer and Sonmez [10] proposed two critical design guidelines for improving the hardness distribution in a material based on optimization procedures. First, a small gap between the mold wall and preformed workpiece led to a small variation in the hardness distribution. Second, sufficient lubrication resulted in a homogeneous hardness distribution. In other words, the coefficient of friction at the mold–workpiece interface exhibited a negative correlation with the degree of variation in hardness distribution. Zottis et al. [12] proposed to evaluate the strain distributions and mechanical performance levels of stretch products by using hardness testing and numerical analysis approaches. These researchers also incorporated the influences of the nonuniform friction between materials and molds into finite element simulations to verify the post-stretching influence as well as the hardness and residual stress distributions. Moreover, with their refined equations and known values of flow stress, they were able to use effective plastic strain to predict material hardness.

This study produced nonaxisymmetric steel elements (crossover U-joints) by using two different processing techniques, namely cold forging and hot forging. This study analyzed and compared the mechanical properties, such as hardness and stretch resistance, of workpieces produced using these two techniques. The material's microstructure was observed in the experiments, and was mutually validated and compared with the material mechanical testing results [13-14]. At least 20 different tribology tests have been used to determine friction coefficients in cold-forging processing. Because such tests have employed different test settings, test methods, and levels of abstraction, comparability among them is questionable. In the present study, six established test principles were compared using the same tribology system. Substantial differences were observed among friction coefficients, and the experimental results suggested that no single tribology type fits all types of cold-forging processing [15].

3. Experiment Design
After cold-forging processing, we tested the material hardness; results were subsequently compared with the output tonnage of devices and a stress–strain diagram generated with a CAE method to analyze the trend of hardness changes (Figure 1).
The experimental material used in the experiment was S45C carbon steel. The raw material has a hardness greater than 190 HB, is a commonly used steel type, has broad applications, and exhibits advantages such as favorable strength, toughness, and performance in turning processing. The material content and mechanical properties are shown in Table 1.

| Main components | C       | Si       | Mn       | S       | P       |
|-----------------|---------|----------|----------|---------|---------|
|                 | 0.42~0.48 % | 0.15~0.35 % | 0.60~0.90 % | ≤0.035 % | ≤0.030 % |

| Mechanical property          | Tensile Strength | Yield Strength | Percent Elongation | Percent Reduction in Area | hardness |
|-----------------------------|------------------|----------------|--------------------|--------------------------|---------|
|                             | ≥58kgf/mm²       | ≥35kgf/mm²     | ≥20%               | ≥45%                     | 167~229HB |

3.1. Material Preprocess

Before the experiment, the materials underwent spheroidizing annealing, phosphate coating, and saponification. After spheroidizing annealing, the hardness of the materials was controlled to 170 ± 10 HV. The spheroidizing annealing treatment reduced the mechanical properties of the materials such as the tensile strength and hardness, and it reduced the impacts from forging, increasing the service life of the mold.

Phosphate coating and saponification enhanced the ductility of the materials and provided the surface with a lubricated coating. During forging, the materials experienced considerable impact and substantial friction against the mold surface, which rapidly increased the temperature. Therefore, a lack of lubrication may result in a failed product. For example, during cold forging, the use of phosphate coating and saponification reduces the resistance of metal flow, reduces deformation loading, controls the surface quality of an object, harmonizes the surface metal flow, reduces the situation in which a workpiece has sticky films, and reduces the surface friction between the material and mold. Using phosphate coating enables a workpiece to be produced more smoothly, and the service life of the mold to be extended.

3.2. Experiment Equipment

An upright forger 650T was used in this study (Figure 2) (the specifications are shown in Table 2).
Figure 2. Upright forger 650T and its specifications.

| SPECIFICATION          |             |
|------------------------|-------------|
| Capacity               | 650 ton     |
| Rating point           | 8 mm        |
| Stroke length          | 200 mm      |
| Die height             | 750 mm      |
| Bolster area (L.R x F.B) | 800 x 800 mm |
| Bolster thickness      | 100 mm      |
| Slide area (L.R x F.B) | 780 x 780 mm |
| Working energy         | 5200 Kg-m@ 35 spm |
| Max .upper die weight  | 1.2 ton     |
| Air source             | 5 Kg/cm²    |

3.3. Condition Settings in CAE Analysis

Deform-3D was adopted in a CAE simulation analysis. Deform-3D is FEA software used for processing simulation systems. It specifically analyzes 3D flow during the formation of metals. It has a wide range of applications in plastic processing, such as forging, extrusion, calandering, free forging, bending, and shearing[16].

Because of discrepancies between CAE analysis results and actual situations, and because analyses must be concluded within reasonable timeframes, some simplifying assumptions must be made regarding CAE, but the essential information must remain intact. The parameter assumptions were as follows:

1. Molds were considered as rigid bodies.
2. Blooms were considered to be plastic and to have homogenous and isotropic properties.
3. The weight, inertia effect, and elastic deformation problems of blooms were disregarded.
4. The interface friction between molds and materials were assumed to follow the constant shear friction law. The friction coefficient was simplified to a constant value.
5. The velocity curve of the molding machines’ motion was simplified to a curve with a constant speed of 10 mm/sec.
3.4. Size of the Forged Product

Figure 3. Dimensions of the forged product.

The specified sizes of cold-forged products are shown in Fig. 3. After products had been processed to their required sizes, other mechanical processing methods were applied; the products conformed to the requirements of an electrical power steering system and were later installed into such a system.

4. CAE Simulation Analysis

4.1. Method Planning

After conducting a computerized adaptive testing simulation analysis to determine factors such as mold cost, mold design limitations, and facility ejection specifications, this study used the method shown in Table 3 on φ32, φ33, and φ34. Consequently, the molding stress was lower, the forging tonnage of the machine was within bearable range, and the mold was under a lower loading, extending the service life.

Table 3. Method planning.

4.2. Parameter Settings in CAE Analysis

The surfaces of molds were finely processed and bright-polished. To simplify the simulation process, the constant shear coefficients were all determined based on the built-in parameters of DEFORM™. Also, R angles smaller than 0.5 r were disregarded, and the smallest R angle was R5. The minimum edge length criterion was set to be 1/3 of the smallest R angle. In this study, a small edge length indicated fine finished products. The minimum edge length adopted in this study was 0.61.

1. Lattice: 40000 (Min Edge Length = 0.61).
2. Material temperature: 20 °C.
3. Mold temperature: 20 °C.
4. Constant shear friction coefficient μ: 0.12.
4.3. CAE Simulation Analysis Results
The CAE simulation analysis in this study used materials with the following diameters: φ32, φ33, and φ34. Figures 4–8 present the CAE simulation analysis results.

Figure 4. First-pass equivalent stress map.

Figure 5. Second-pass equivalent stress map.

Figure 6. Third-pass equivalent stress map.
The impacts of a hammer and the upper mold falling from a certain height were simulated to create plastic deformation in the materials for molding. The area between the blue and red blocks shown in the figures was utilized to evaluate the received stress and determine whether problems such as overly large stress or stress concentration occurred during the processing. The area was also used to understand if a forging piece was broken or if spew occurred. Figure 5 shows that the blue area received less stress than did the red area.

The forging streamlines formed in the CAE simulation were utilized to evaluate whether the method planning was adequate. An uneven streamline distribution reveals uneven metal flow, resulting in reduced mechanical performance, especially the impact toughness and fatigue performance. The actual product may have had such problems as misalignment, folding, and parting surface cracks. The
simulation map in Figure 9 shows that the forging streamlines were smoothly distributed, revealing that the mold design and method planning of the present study were reasonable and would not lead to defects during production.

4.4. CAE Analysis of the Machine Output Tonnage

Figures 10–14 present the simulated machine output tonnage. The tonnage of φ32, φ33, and φ34 varied slightly. To verify the simulated data, cold forging was conducted, and the results were compared with the simulated data.

Figure 10. First-pass machine output tonnage.

Figure 11. Second-pass machine output tonnage.

Figure 12. Third-pass machine output tonnage.

Figure 10 shows that when the machine stamping process reached approximately 24 mm, the tonnage of φ34 was the highest. When mapping the simulation position in the CAE simulation, this study saw
that before the stamping process reached 24 mm, the molding stress was almost completely concentrated at the nosing. Therefore, this study inferred that the reduction rate correlated to the machine output tonnage of the nosing. After the stamping process reached 24 mm, the tonnage of φ32 was the highest. Therefore, this study inferred that the material deformation of φ32 extruding to φ34.5 was larger than that from φ34 extruding to φ34.5, and the machine output tonnage was also higher.

As shown in Figure 11, when the machine stamping process was approximately 15.8 mm, the tonnage of φ34 was the highest. For the same reasons, a large reduction rate led to high machine output tonnage. When the machine stamping process reached approximately 15.8 mm, φ32 demonstrated the highest output tonnage. The fifth-pass machine output tonnage simulated using CAE was the highest for φ32; however, the differences were small among the various diameters. The reason may be that during the previous passes, because the deformation from φ32 to φ34.9 was larger than those of the other diameters, the forging streamline should have been denser and its mechanical characteristics enhanced. Therefore, the machine output tonnage was higher than that of the other diameters.

5. Experiment Results

5.1. Comparison of Finished Product and Methods
The following figures show the finished product after cold forging. Their measurements revealed that the sizes of φ32, φ33, and φ34 all satisfied the designed size of the method, and the errors were within the set tolerance. The first-pass of φ34 showed that the phosphate coating at the nosing was completely worn, whereas that of φ32 still had some phosphate coating. A comparison of the CAE simulation and the actual results showed that the largest diameter resulted in the largest stress in the nosing and caused considerable wear in the phosphate coating and mold.
5.2. Comparison of Finished Product and Methods

After heat embedment, this study used an optical microscope to observe the metallographic change before and after forging. Figure 17(a) shows the metallographic change after forging. The white tissue resembles ferrite, and the black, austenite. During the formation process, the metallographic tissues were extruded, resulting in their crystal grain shape changing from their original rough and large grain boundaries to smaller and narrower boundaries.

Figure 17(b) illustrates the distribution of the forging streamlines, whereby the flow direction was the same as that of the CAE simulation (Figure 9). Additionally, no misalignment, folding, or parting surface cracks were observed. The metal material flowed homogeneously, and the distribution of the forging streamlines was smooth. Inspecting the metallographic revealed that the tissues of the materials became tighter after extrusion, which subsequently enhanced the mechanical performance.
Figure 18. Hardness test locations.

Table 4. Hardness measurements.

| Location | φ32   | φ33   | φ34   |
|----------|-------|-------|-------|
| A1       | 256   | 263   | 278   |
| A2       | 264   | 274   | 290   |
| A3       | 271   | 279   | 296   |
| Average  | 263.7 | 272   | 288   |
| B1       | 239   | 249   | 255   |
| B2       | 250   | 262   | 273   |
| B3       | 253   | 267   | 288   |
| Average  | 247.3 | 259.3 | 272   |
| C1       | 264   | 256   | 249   |
| C2       | 275   | 267   | 256   |
| C3       | 278   | 275   | 267   |
| Average  | 272.3 | 266   | 257.3 |

Table 4 lists the hardness measurements. As shown, the hardness at locations A1, B1, and C1 was lower than that at A3, B3, and C3, respectively. A comparison with the CAE simulation results revealed that when the internal molding stress was low and the deformation small, the internal hardness was lower than the external hardness. This trend was also observed in φ32, φ33, and φ34.

6. Summary and Conclusions

1. The experiment results showed that using an intermediate shaft of varying diameters could reflect the hardness distribution in a workpiece undergoing cold forging. In other words, an ideal hardness in a forging piece could be achieved without heat treatment.
2. The first-pass CAE simulation revealed that the φ34 nosing into φ23.1 required a molding stress larger than the φ32 nosing into φ23.1. A comparison of the hardness of the simulation and finished product revealed that it had undergone cold forging. Moreover, this study learned that the locations in the CAE simulation that reflected large stress demonstrated high hardness after cold forging.
3. The actual hardness values revealed that after cold forging, the internal hardness of a round bar material was lower than the external hardness. Because the exterior impact was larger than that in the interior, the exterior experienced larger stress, resulting in higher hardness.
4. The hardness data in Figure 18 and Table 3 show that the hardness at the end of location A on φ34 was higher than that at the end of location A on φ32. However, the hardness at the end of location C on φ34 was lower than that at the end of location C on φ32. The CAE simulation results revealed that when the material of the cold forging piece experienced large deformation, its hardness increased (given that the materials and molds were the same; only the diameters of the material were different).
5. The hardness at the end of location A on φ34 was higher than that at end of location C, whereas the situation showed the reverse for φ32. In other words, the hardness at the end of location A on φ32 was lower than that at the end of location C on φ32. The machine output tonnage curve graph and
equivalent stress graph of the CAE simulation revealed that because the energy required to extrude from φ32 to φ35 was large, it created relatively high hardness.

6. Although an ideal hardness could be achieved through the application of materials of different diameters, the locations of stress concentration should be considered to prevent large deformation that wears the phosphate coating on the surface of materials and subsequently wears the mold or reduces their service life.

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