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단조기어 정밀도 향상을 위한 연구

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A Study to improve dimensional accuracy of forged gear

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Abstract

The dimension of forged part is different from that of die. Therefore, a more precise die dimension is necessarys to produce the precise part, considering the dimensional changes from forging die to final part.

In this paper, both experimental and FEM analysis are performed to investigate the effect of several features including die dimension at each forging step and heat-treatment on final part accuracy in the closed-die upsetting. The dimension of forged part is checked at each stage as machined die, cold forged, and post-heat-treatment steps. The elastic characteristics and thermal influences on forging stage are analyzed numerically by the DEFORM-2D™. The effect of residual stress after heat-treatment on forged part could be considered successfully by using DEFORM-HT™.

Key Words : Cold Forging (냉간 단조), Spur Gear (스퍼 기어), Residual Stress (잔류 응력), FEM (유한요소법) Involute Curve (인벌류트 곡선), 배압성형(Back Pressure Forming)

1. Introduction

The high dimensional accuracy of cold forged part has been a goal closely related with the economy of forging industry since such accuracy enables the production of more valued forging parts. Since the transmission for new generation car adopts high speed transmission, more gears were used and need to be manufactured cheaper and cheaper. Therefore, forging technology for precision gear has been concentrated on related industries, mainly helical gear. Forging of automobile gears, especially, must be developed about many process variables, as shown in Fig. 1. Therefore, many researchers studied tried to develop by many researchers [1-6]. Lee [7] et. al. investigated the dimensional changes of die and workpiece during forging stages and Cho [8] et. al. studied about the distortion of part by the heat-treatment.

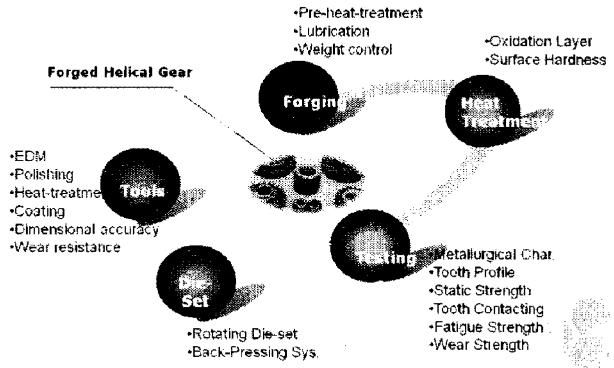

Fig. 1 Forging process variables for helical gear forging

The dimension is continuously changed during cold forging practice due to the elastic characteristics of the die and workpiece and thermal influences on forging stage. Therefore a more precise die dimension needs to produce the precise part, considering the dimensional changes from forging die to final part.

In this paper, both experimental and FEM analysis are

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performed to investigate the effect of several features including die dimension at each forging step and heat-treatment on final part accuracy in the closed-die upsetting. The dimension of forged part is checked at each stage as machined die, cold forged, and post-heat-treatment steps. The elastic characteristics and thermal influences on forging stage are analyzed numerically by the DEFORM-2D™. The effect of residual stress after heat-treatment on the forged part could be considered successfully by using DEFORM-HT™.

Also, the dimensional change and residual stress during the heat treatment also have been investigated by using the spur gear. These characteristics of forged gear were compared with the machined gear, specially, the effect of residual stress during the heat treatment. Since the residual stresses of forged gear and machined gear were different each other, the amount of dimensional changes would not be same. The three measuring points were selected along the height of tooth. Surface residual stresses were measured by the X-ray stress analyzer. (Stresstech Oy Co., Finland) Changes of involute profile and residual stress were traced more accurately by the tracing same specimen

2. Experiment and FEM analysis

2.1 Experimental details

The closed-die upsetting of a cylindrical billet was chosen for experimental and FEM analysis, as shown in Fig.2. Tool steel, AISI H-13, was used as die material. The workpiece material was SAE4118H, which was one of the popular alloy steels for gears. The workpiece was pre-treated with a spheroidized annealing and a Zn-phosphated lubrication before cold forging. The low-speed-hydraulic compressive-testing-machine (Tinius Olsen 200ton) was used since high machine rigidity could minimize the elastic deformation from the machine. The applied load was 100,000kgf, which was over the critical load [9].

And then, the forged parts were treated by heat treatment cycle, as shown in Fig. 3. The radii of part were measured at each step; as machined die, as forged part, and after heat treatment. Fig. 4 shows the measuring positions.

2.2 FEM analysis

The dimensional differences between and forged part during forging stage were generated by the elastic deformation of die, elasto-plastic characteristics of workiece and thermal contraction of forged part. Therefore, the dimensional changes from die to forged part were simulated on condition that the die was elastic and workpiece was elasto-plastic material. And the additional deformations of workpiece during unloading and ejecting stage were considered and thermal influence was calculated during whole forging stage [9]. The more details for FEM simulation conditions and material properties were written in ref. [9].

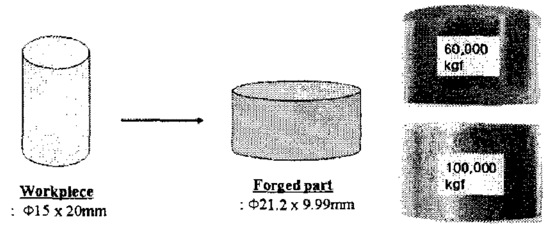


Fig. 2 Dies, workpiece and forged part

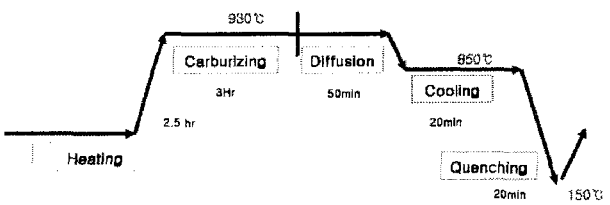


Fig. 3 Heat treatment cycle for forged part

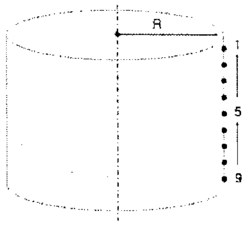


Fig. 4 positions measuring radius at each step

3. Results and discussions

3.1 Dimensional changes during forging stage

When the additional deformation of workpiece during unloading and ejecting stage and thermal influences were considered, the dimensional changes estimated by FEM were compared with experimental results, as shown in Table 1. The differences between experiment and FEM analysis were within the 10 μm. The amounts of dimensional change were different at each position. The dimensional changes generated by the elastic characteristics during forging stage were about 0.039 ~ 0.052mm. The difference amounts are reached at the range from 0.372% to 0.490% of die dimension when the dimensions of die were criteria. Since these values were different by the applied force and amounts of secondary amount, the each simulation should be performed with each model and conditions [9].

Table1: Dimensional changes between die and forged part

Position No.	Machined Die[A]	Forged Part [B] (Exp.)	Difference [(B-A)/A](%)
1	10.602	10.641	0.372
2	10.603	10.652	0.462
3	10.609	10.661	0.485
4	10.615	10.665	0.462
5	10.616	10.668	0.49
6	10.617	10.668	0.478
7	10.617	10.665	0.459
8	10.616	10.662	0.435
9	10.616	10.655	0.372

Position	FEM analysis		
No.	Loading	Unloading	Ejecting
1	10.675	10.625	10.657
2	10.685	10.629	10.655
3	10.694	10.636	10.664
4	10.701	10.641	10.67
5	10.703	10.643	10.67
6	10.702	10.643	10.672
7	10.698	10.641	10.667
8	10.693	10.639	10.667
9	10.686	10.637	10.667

Specially, since secondary yielding makes effects into the additional dimensional changes of forged part, the elastic characteristics of die must be considered during whole forging stages. The consideration for unloading and ejecting stage in FE simulation affects the residual stress of forged part. Residual stress makes an effect the dimensional changes and then affects into the dimensional changes in FE simulation for heat treatment process. Fig. 5 shows the simulated values of residual stress for forged part.

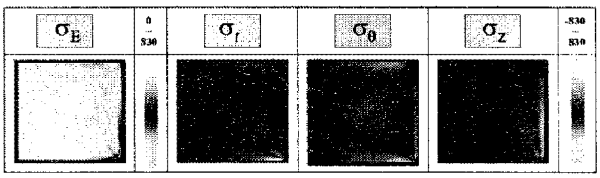


Fig. 5 Residual stress of forged part predicted by FEM analysis

3.2 Dimensional changes by heat treatment

The dimensions of forged part were changed once more by the heat treatment. The measured and simulated dimensions of the final part after heat treatment were shown in Table 2. DEFORM-HT was used to simulate the heat treatment and quenching processes for forged part using the model simulated by the DEFORM-2D^{TM}. Therefore, the residual stresses, which are shown in Fig. 5, considered in heat treatment simulation. Fig. 6 shows the volume fraction of martensite at each position. Since the temperature descend at surface is faster than that of at center, the martensite volume fraction at surface is higher than that of at center.

Table2: Dimensional changes before and after heat treatment

Position No.	Experiment		
	Forged Part [C]	After Heat Treatment [D]	Amount of Change [(D-C)/C] (%)
1	10.641	10.663	0.202
2	10.652	10.671	0.179
3	10.661	10.681	0.193
4	10.665	10.686	0.197
5	10.668	10.688	0.179
6	10.668	10.689	0.192
7	10.665	10.687	0.2
8	10.662	10.688	0.241
9	10.655	10.676	0.195

Position No.	Experiment		
	Forged Part	After Heat Treatment	Amount of Change (%)
1	10.675	10.625	10.657
2	10.685	10.629	10.655
3	10.694	10.636	10.664
4	10.701	10.641	10.67
5	10.703	10.643	10.67
6	10.702	10.643	10.672
7	10.698	10.641	10.667
8	10.693	10.639	10.667
9	10.686	10.637	10.667

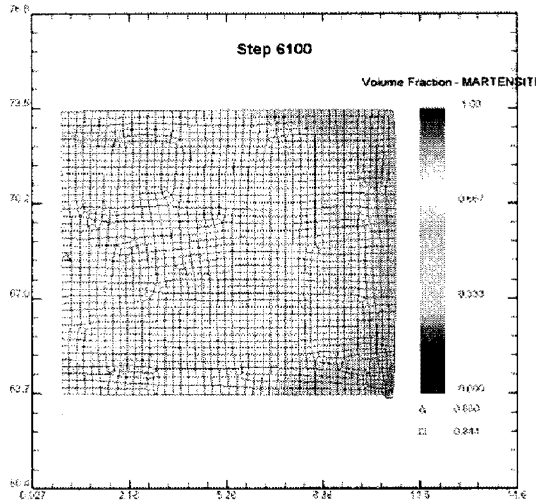


Fig. 6 Distribution of martensite volume fraction after quenching

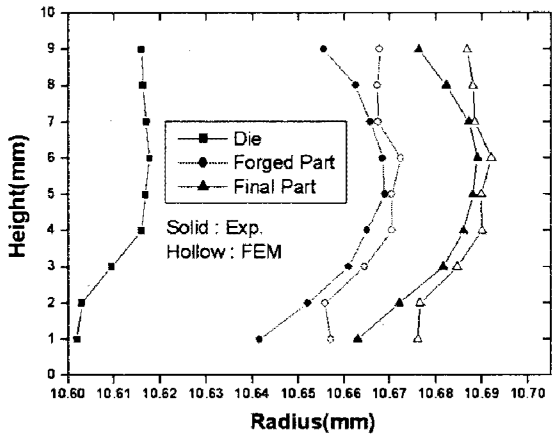


Fig.7 Dimensional changes of die and parts

3.3 Changes of Dimension and residual stress by heat treatment of spur gear

The dimensions of forged part were changed once more by the heat treatment. The measured involute profiles of forged gear and machined gear before and after heat treatment were shown in Fig. 7. The residual stresses of forged gear and machined gear were measured and used in calculating the distortion of involute profile during FE simulation of heat treatment. Fig. 8 shows the residual stresses all the two gears before and after heat treatment at 3-measuring-point. Forged gear had some compressive residual stresses applied on forging stage. The compressive stress been increased by the heat treatment. On the other hand, the surface residual stress of machined gear changed from the tensile stress to compressive stress. The tensile stress has been applied on tooth surface by the machining tool during the gear shaping process. The compressive stress has been accommodated into the machined gear during heat treatment. The residual compressive stresses of two gears after heat treatment were almost same level, as shown in Fig.9. Differences of residual stress before and after heat treatment in the case of machined gear were larger than that of the forged gear. Therefore, dimensional change of machined gear was larger than that of forged gear up to the 20μm. Since residual stress affected into dimensional changes before and after heat-treatment, the residual stress values simulated by the FEM analysis should be verified with the experimental results, as shown in Fig. 10. The simulated residual stress was lower than that of measured values within the range of 30 MPa, when the residual stress before heat-treatment was considered in FE simulation.

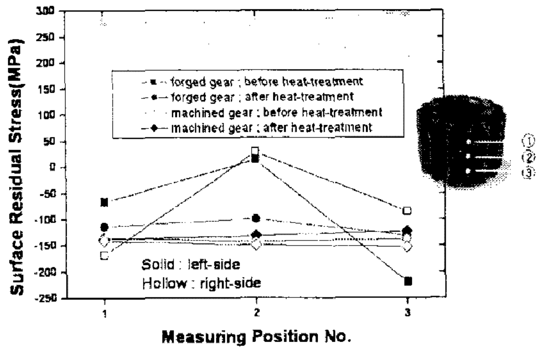


Fig. 8 Residual stresses all the two gears before and after heat treatment at 3-measuring-point

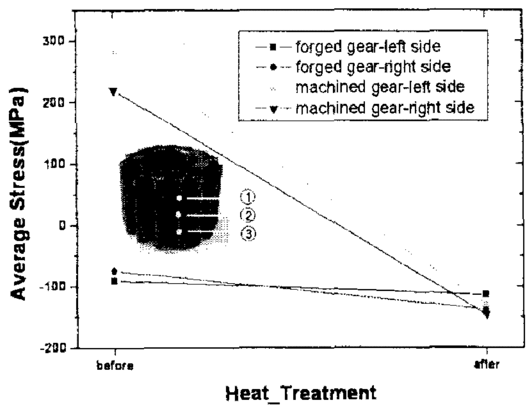
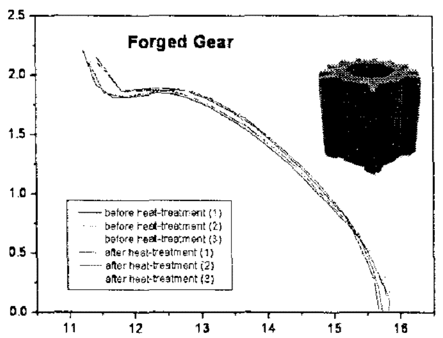
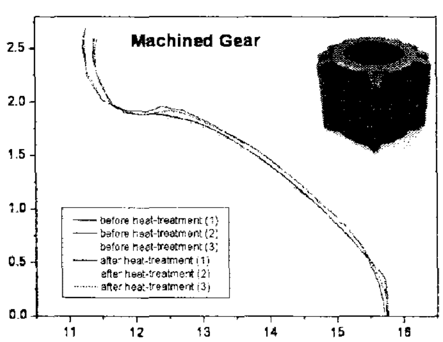


Fig. 9 Average residual stresses of the two gears before and after heat treatment





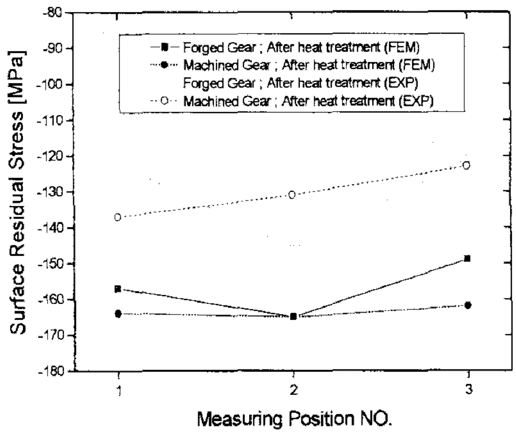


Fig. 10 Comparisons of measured and calculated residual stress during heat treatment

4. Discussions

The designed radius of model was 10.6 mm. As shown in the experimental results, when a machined die was within the range of 10.602 ~ 10.617mm, the dimension of final part was 10.663~ 10.689mm. Finally, the dimensions of final part after heat-treatment differ from the machined die within the range of 0.061 ~ 0.072mm. The radius changes of from die through forged part to final part at each position were shown in Fig. 7. The amounts of dimensional changes on forging stage were larger than that of heat-treatment process on at least this model. The results of experiment and FEM analysis showed similar tendencies. The dimensional changes were larger at middle area of forged part in the vertical axis due to the much larger stress changes. The average amount of dimensional changes was about 0.50% during forging stage and 0.20% at heat-treatment when the die dimension was criteria.

For the dimensional control of forged gear within the micrometer, both elastic characteristics of die and forged part during forging stage and thermal characteristics by the heat treatment should be quantified accurately. And then, the dimensional changes between die and final gear should be considered into the real die for gear forging. These dimensional changes could be analyzed quantitatively by experimental and FE analysis, comparing with thermal characteristics of the machined gear. Differences of residual stress before and after heat treatment in the case of machined gear were larger than that of the forged gear. Therefore, dimensional change of machined gear was larger than that of forged gear up to the 20μm. The simulated residual stress was lower than that of measured values within the range of 30 MPa, when the residual stress before heat-treatment was considered in FEM analysis.

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