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Original Paper

Design of the trimming process of an Al6061 alloy bolt head using finite element analysis and the taguchi method

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Abstract: In this study, we designed a trimming process for an Al6061 alloy bolt head while considering the shear surface quality and shear load. The process was optimized using finite element analysis (FEA) and the Taguchi method. The blade radius of the punch, land width of the bottom die, and stop distance between the punch and the bottom die were selected as design parameters. FEA was conducted using DEFORM-2D, a commercial FEA software program. The shear and fracture behavior of the material during trimming was analyzed using the Cockcroft-Latham ductile fracture criterion. To verify the validity of the proposed design, a trimming experiment was performed on the M12 Al6061 alloy bolt for a helideck fastening by applying the optimum process conditions derived from the FEA results. As a result, a shear surface shape extremely similar to the FEA result could be obtained, which confirmed the validity of the proposed design method. One would expect that the proposed design method can be widely applied to design bolt trimming processes with various specifications other than M12.

Keywords: Al6061 alloy bolt, Trimming process, Finite element analysis, Taguchi method, Ductile fracture criterion

1. Introduction

Trimming refers to the shearing process used to fabricate a final product with specific shape by removing unnecessary parts from the edge of a forged product. It is used to produce various industrial components, such as bulk and sheet products. During trimming process, post-treatment is required when the dimensional accuracy of the shear surface is poor or excessive burrs are created. This degrades the price competitiveness due to an increased production cycle. Therefore, it is extremely important to secure the shear surface quality during trimming. In this study, we designed a trimming process for an M12 hexagonal bolt made of Al6061 alloy for a helideck fastening.

Thus far, many studies on the trimming process have been conducted. Choi *et al.* **[1]** examined the effects of clearance and the die inclined angle on the shear surface quality during trimming of ultra-high strength steel sheets. Lee *et al.* **[2]** investigated the effects of clearance, blade radius of the punch and die, blank holding force on the roll-over and effective shear surface during trimming of automotive door latches and derived the optimum trimming process conditions using the Taguchi method. Li **[3]** experimentally evaluated the effects of the shear angle, punch blade radius, and clearance on the shear surface quality and burr height during shearing of an aluminum sheet; they confirmed that a shear surface with excellent quality can be obtained within a specific shear angle range, regardless of the clearance and punch blade radius.

Han *et al.* **[4]** conducted finite element analysis (FEA) by applying ductile fracture models to the trimming process of ultra-high strength hot stamping components and compared the results with the experimental results. They also observed crack formation based on the analysis results and examined the effects of clearance, shear angle, and punch blade radius on the shear surface shape. MacCormack *et al.* **[5][6]** optimized the bolt trimming punch shape while considering service life of the die using FEA. They also investigated the effect of the stop distance between the punch and the die on the shear load and shear quality caused by the knockout pin. Cho *et al.* **[7]-[9]** proposed a die design method for improving shape defects during flange bolt trimming. They also performed a multi-stage cold forging process designed to improve productivity and minimize chips that occur in large quantities during the production of non-axisymmetric cam bolts.

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Most previous studies focused on sheet trimming, or did not consider the design of the bottom die shape for bolt trimming. Moreover, some prior studies did not experimentally verify the critical damage value when ductile fracture criteria were used to simulate the shearing mechanism of the material.

Therefore, we conducted FEA based on the mechanical properties and critical damage value obtained from material tensile tests, and we designed a trimming process for an M12 bolt head made from Al6061 alloy. The blade radius of the punch, land width of the bottom die, and stop distance between the punch and the bottom die were selected as design parameters. In addition, the process was optimized using the Taguchi method for the shear surface quality and forming load. The validity of the proposed design method and the FEA results were verified by performing the trimming experiment based on the optimum process conditions derived from the FEA results and subsequently examining the shear surface.

2. Conditions of Finite Element Analysis

2.1 Mechanical properties of the material

The material used in this study was Al6061-T0 alloy with formability improved through annealing. A tensile test was conducted in accordance with the KS B 0802:2003 standards to determine the mechanical properties of the material. The gauge length and diameter of the specimen were 25 mm and 5 mm, respectively. **Table 1** shows the mechanical properties determined from the tensile test.

The Cockcroft-Latham ductile fracture criteria were used to evaluate the shear and fracture behavior of the material during trimming based on results in previous studies **[6][10][11]**. Many theories were proposed to predict ductile fracture. The Cockcroft-Latham model is known to be easily applicable and produce accurate results for the bolt trimming process.

$$C_1 = \int_0^{\bar{\varepsilon}_f} \sigma_{max} d\bar{\varepsilon} \tag{1}$$

where $\bar{\varepsilon}$ is the effective strain, σ_{max} is the maximum principal stress, $\bar{\varepsilon}_f$ is the effective strain at fracture, and C_1 is the critical damage value. The critical damage value of Al6061-T0 was found to be 74.4 from the tensile test results.

2.2 Finite element analysis model

The trimming process was analyzed using DEFORM-2D, a commercial FEA software program. The analysis model was selected based on the cross section A-A', where the maximum scrap of the material occurs during trimming, as shown in **Figure 1**. During analysis of the trimming process, axisymmetric models can be used to reduce the analysis time compared to 3D models and they are useful in quantitatively evaluating formation of non-uniform burr along the shear surface **[3][5]**. **Figure 2** shows the axisymmetric FEA model used for the trimming analysis. Smaller meshes were used in the shear zone to increase the accuracy of the description of shear and fracture. As a result, 8,494 nodes and 8,230 elements were generated. Moreover, the deformation history accumulated during forging was imposed on the material by performing the analysis of the multi-stage cold forging process prior to trimming analysis **[12]**. The friction constant (m) was determined to be 0.1 based on results from a previous study **[11]**, and the trimming punch speed was set to 100 mm/sec based on the specifications of cold formers for prototype production.

Table 1: Tensile properties of Al6061-T0

Material	Y.S. [MPa]	T.S. [MPa]	El (%)
Al6061-T0	**66**	**150**	**33.3**
Flow stress curve		**Critical damage value**	
$\bar{\sigma} = 248.5(\bar{\varepsilon})^{0.1914}$		**74.4**	

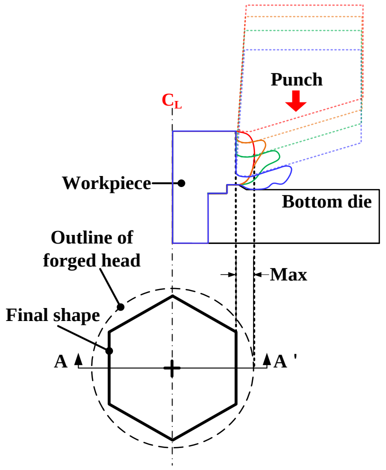


Figure 1: Description of the cross-section for FE-analysis

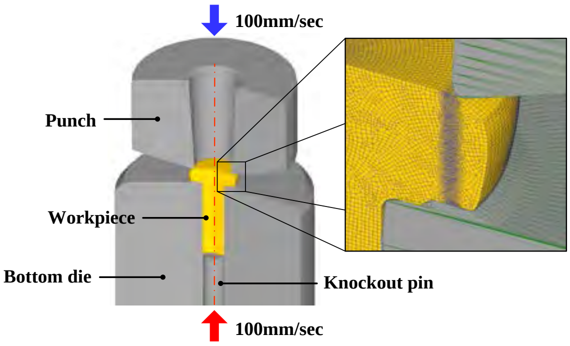


Figure 2: FE-model of the trimming process

2.3 Design parameters and orthogonal array table

The trimming process for the Al6061 bolt head was optimized using the Taguchi method. The blade radius (*BR*) of the punch, land width (*LW*) of the bottom die, and the stop distance (*SD*) between the punch and the bottom die were selected as design parameters, as shown in **Figure 3**. Unlike sheet trimming, which is completed in a single shearing process, bolt trimming is divided into the two shearing processes as shown in **Figure 4 [6].** In the first sequence, the punch performs shearing up to the determined stop distance while pressing the material. In the second sequence, the final shearing process is performed while the knockout pin installed inside the bottom die pushes on the connection between the bolt and scrap (opposite the punch movement). If the end of the trimming punch align with the end of the bottom die land section (*LW* = *0*) as shown in **Figure 5**, a relatively large crack zone occurs in the middle of the shear surface, thereby degrading the shear surface quality. According to results from a previous study, applying a compressive hydrostatic stress during trimming delays cracking occurrence and increases the effective shear surface **[1]**. Therefore, cracks must be suppressed during shearing to secure a sound shear surface until final shearing by applying a reaction force against the trimming load to the bottom die. Accordingly, the land width of the bottom die was offset by 0.5, 1.0, and 1.5 mm from the shear surface along the bolt head. The application ranges of the punch blade radius and the stop distance were determined from the results in a previous study **[5]**. To generate the L_9 (3^3) orthogonal array table, all parameter ranges were divided into three levels. **Tables 2** and **3** show the design parameters with three levels and L_9 (3^3) the orthogonal array table created for using the Taguchi method, respectively. FEA was conducted based on the orthogonal array table.

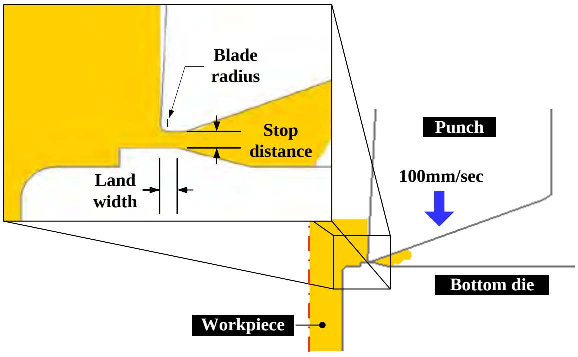
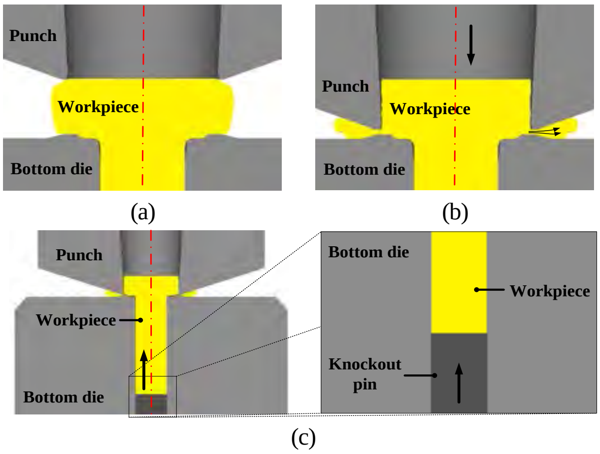


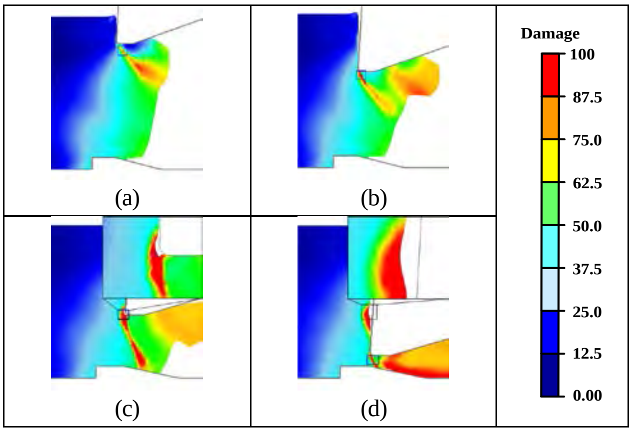
Figure 3: Design parameters required in the trimming process



(a) (b)

(c)

Figure 4: Schematic illustration of the trimming process: (a) initial state, (b) 1^{st} sequence, and (c) 2^{nd} sequence.



(a) (b)

(c) (d)

Figure 5: Crack propagation during trimming: (a) 16.6% stroke, (b) 39.1% stroke, (c) 66.2% stroke, and (d) 98.0% stroke.

Table 2: Design parameters and their values by level

Parameters	Level1	Level2	Level3
Blade radius(*BR*) [mm]	**0.2**	**0.3**	**0.4**
Land width(*LW*) [mm]	**0.5**	**1.0**	**1.5**
Stop distance(*SD*) [mm]	**0.25**	**0.5**	**0.75**

Table 3: L_9 (3^3) orthogonal array table

Simulation #	*BR*	*LW*	*SD*
1	**0.2**	**0.5**	**0.25**
2	**0.2**	**1.0**	**0.50**
3	**0.2**	**1.5**	**0.75**
4	**0.3**	**0.5**	**0.50**
5	**0.3**	**1.0**	**0.75**
6	**0.3**	**1.5**	**0.25**
7	**0.4**	**0.5**	**0.75**
8	**0.4**	**1.0**	**0.25**
9	**0.4**	**1.5**	**0.50**

3. Results of Finite Element Analysis

3.1 Application of the Taguchi method through FEA

The shape defects (DF_{shape}) and peak trimming load ($Load_{peak}$) were set as objective functions to examine the effects of the design parameters (selected above) on the shear surface quality and shear load. The shape defects are shown in **Figure 6** and defined in **Equation (2)** as follows:

$$DF_{shape} = A_R + A_U + A_B \qquad (2)$$

where A_R, A_U, and A_B represent the roll-over, under-filling, and burr areas, respectively.

Figure 7 shows the trimming load curve as a function of the punch stroke. As shown in the figure below, multiple shearing and fractures take place during trimming. The peak trimming load occurred during the initial shearing because it had the maximum shear area. Later, the load gradually decreased with the periodic increase and decrease according to the punch stroke. As it is favorable when both the shape defects and peak trimming load are smaller, the signal-to-noise (SN) ratio was calculated by applying the loss function of the-smaller-the-better characteristics in **Equation (3)**:

$$SN = -10log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (3)$$

where y is a measured value and n is the number of measurements.

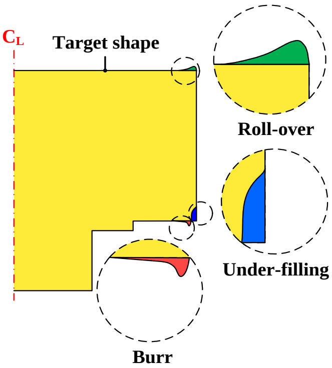


Figure 6: Description of shape defects

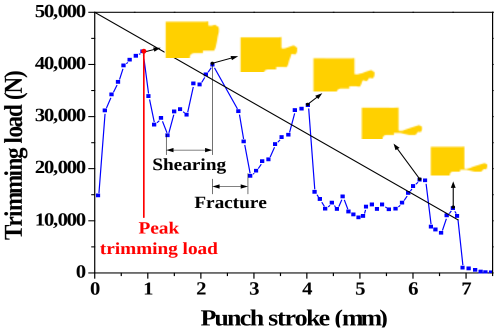


Figure 7: Punch stroke-trimming load curve

Table 4 and **Table 5** show the results of FEA and the Taguchi method to the shape defects and peak trimming load, respectively. **Figure 8** shows the effect of each parameter on shape defects and peak trimming load. The process parameter that had the greatest impact on shape defects was the blade radius, followed by the stop distance and land width. The process conditions that created the highest SN ratio were 0.2 mm blade radius, 1.0 mm land width, and 0.25 mm stop distance.

The peak trimming load showed high sensitivity only to the shape of the punch (blade radius), and the influence of land width and stop distance were insignificant. The SN ratio of the trimming load tended to be inversely proportional to the blade radius. This is because the contact area between the punch and the material increases as the blade radius increases [5]. Therefore, the optimum process conditions for the trimming load were 0.2 mm blade radius, 1.5 mm land width, and 0.75 mm stop distance.

The optimum process conditions of the land width and stop distance were selected based on the shape defects that exhibited relatively high sensitivity. Therefore, the optimum conditions in the trimming process derived from the FEA results with the Taguchi method were 0.2 mm blade radius, 1.0 mm land width, and 0.25 mm stop distance.

Table 4: FEA results for DF_{shape}

Simulation #	DF_{shape} [mm^2]	SN ratio
1	0.046	26.7448
2	0.044	27.1309
3	0.159	15.9721
4	0.374	8.5426
5	0.193	14.2889
6	0.120	18.4164
7	0.229	12.8033
8	0.156	16.1375
9	0.496	6.0904

Table 5: FEA results for $Load_{peak}$

Simulation #	$Load_{peak}$ [N]	SN ratio
1	42,414	-92.5502
2	42,414	-92.5502
3	42,290	-92.5248
4	43,108	-92.6912
5	43,079	-92.6853
6	43,102	-92.6899
7	44,056	-92.8801
8	43,980	-92.8651
9	44,068	-92.8825

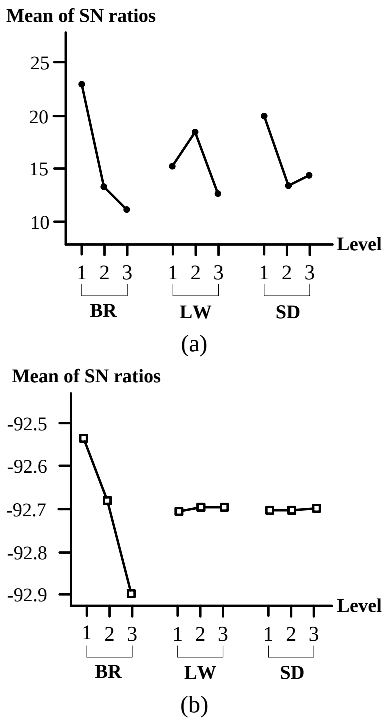


Figure 8: Main effect plots for objective functions: (a) shape defects and (b) peak trimming load

3.2 FEA results for the optimum process condition

Based on the above results, FEA was conducted. **Figures 9** and **10** show the damage distribution and hydrostatic stress distribution of shear surface at various punch stroke values, respectively. Although locally high damage values appeared near the middle of the shear surface, a good shear surface without crack defects formed during preliminary analysis was obtained. This can be attributed to the compressive hydrostatic pressure that acted on the shear zone between the punch and the material.

Moreover, as with previous studies, final shearing by the knockout pin was performed while cracks occurred on the shear surface A-A' with a certain angle. However, the 'dragged through' phenomenon mentioned in a previous study was not observed **[6]**. This appears to be because analysis was conducted in the previous study without considering the accurate critical damage value of the material through experiments. As the shape of the shear surface varies depending on the critical damage value during trimming, it is very important to acquire accurate mechanical properties and a critical damage value for the material through experiments.

Figure 11 and **Table 6** show the analysis results for the shear surface shape and trimming load. Satisfactory shape defects and peak trimming load results were obtained.

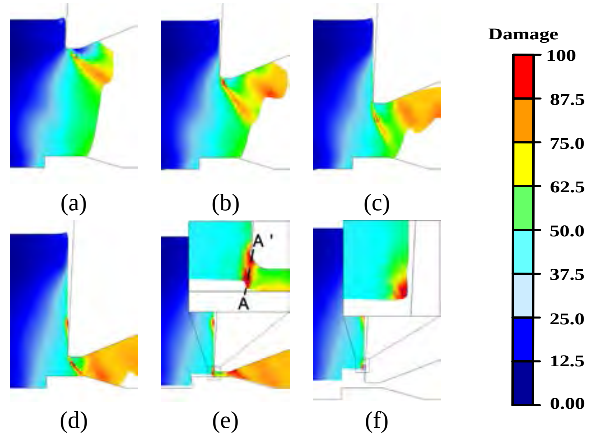


Figure 9: Damage distribution in the optimum process condition: (a) 19.9% stroke, (b) 40.4% stroke, (c) 60.9% stroke, (d) 88.7% stroke, (e) shear by KO_{pin}, and (f) final state.

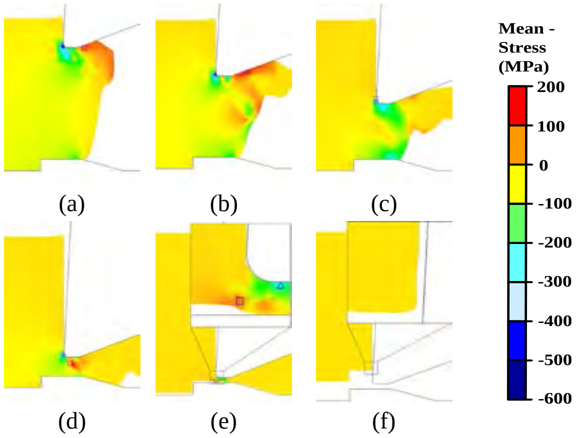


Figure 10: Mean stress distribution in the optimum process condition: (a) 19.9% stroke, (b) 40.4% stroke, (c) 60.9% stroke, (d) 88.7% stroke, (e) shear by KO_{pin} and (f) final state.

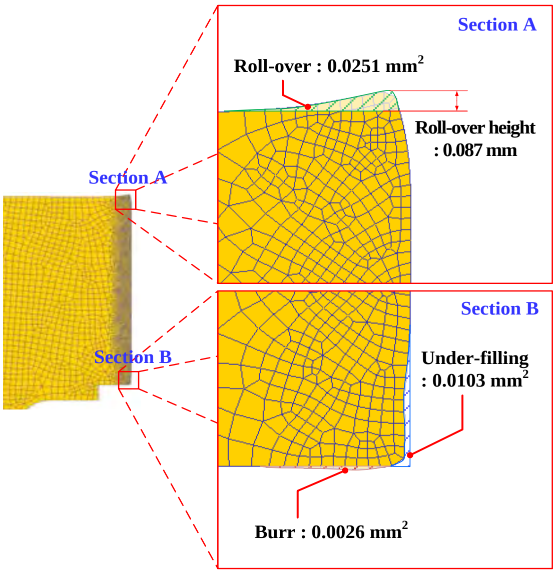
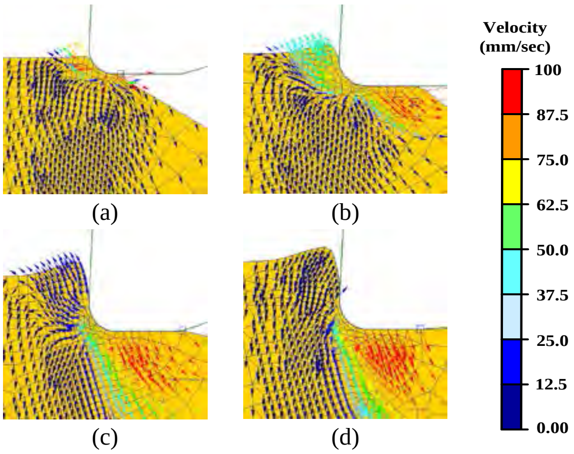


Figure 11: Sheared plane profile in FEA

Table 6: FEA results showing optimum trimming conditions

Objective functions	Values	
Shape defects (mm^2)	**Roll-over**	**0.0251**
	Under-filling	**0.0103**
	Burr	**0.0026**
	Total	**0.038**
Peak trimming load (N)	**42,414**	



(a) (b) (c) (d)

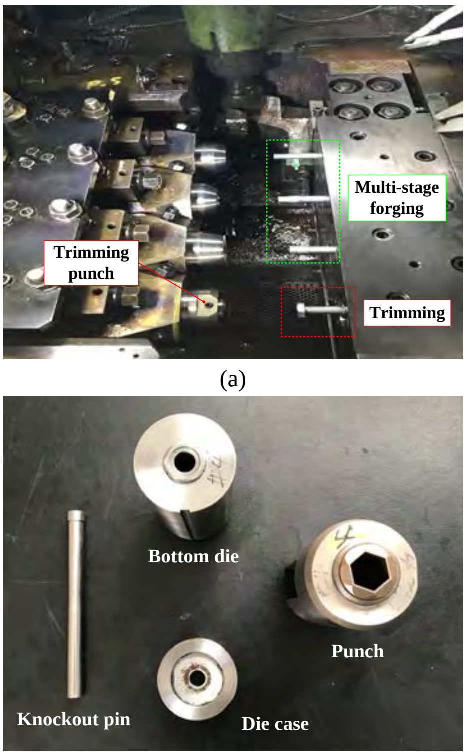
Figure 12: Velocity distribution on the upper part of the bolt head: (a) 0.025% stroke (b) 0.15% stroke (C) 0.3% stroke (d) 0.45% stroke.

However, as shown in **Figure 12**, roll-over occurred on the top of the bolt head due to the indentation of the punch. In general, during sheet trimming, roll-over occurs along the punch load direction due to a bending moment. On the other hand, in the case of a bolt trimming process, the material around the punch blade section rises as much as the volume of the punch's penetration due to the reaction force from the bottom die.As roll-over is proportional to the blade radius, it seems desirable to design the blade radius of the punch to be as small as possible.

4. Trimming Experiment

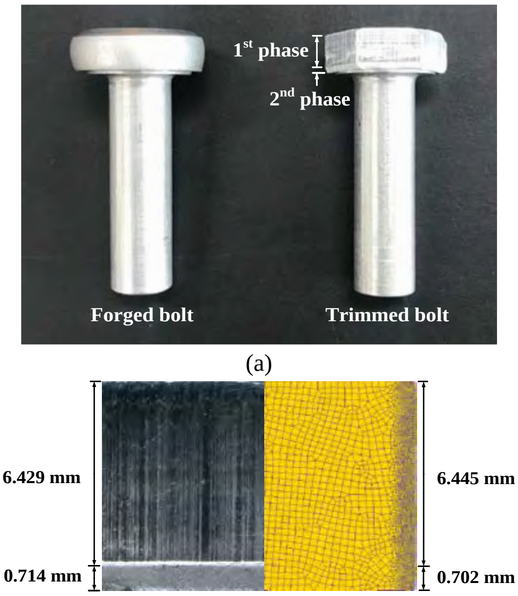
To verify the validity of the design method and FEA results presented in this study, we performed a trimming experiment on an M12 Al6061 alloy bolt head using the aforementioned process conditions. **Figure 13** shows the cold former and trimming dies used in the experiment. In the same manner as in the analysis conditions, the bolt head was formed by performing a multi-stage cold forging process prior to trimming. The process conditions and material properties are the same as those used in the FEA simulations.

Figure 14 shows the cross-sectional shape and dimensions of the product produced with the trimming experiment. The figure shows that the cross-sectional shape of the product obtained through trimming agrees well with the FEA results. A high quality product without large defects that meets the standard dimensions was obtained, confirming the validity of the proposed design method.



(a) (b)

Figure 13: Trimming experiment of Al6061 alloy bolt head: (a) cold-former and (b) brimming dies



(a) (b)

Figure 14: Trimming experiment results: (a) shape of the trimmed bolt and (b) comparison of shear section C with the FEA results.

5. Conclusion

In this study, the trimming process of an M12 aluminum alloy bolt head for a helideck fastening was designed using FEA and the Taguchi method. The design parameters selected for optimizing the process were the blade radius of the punch, land width of the bottom die, and stop distance between the punch and the die.

The SN ratio results obtained by the Taguchi method show that the process parameter with the greatest impact on shape defects was the blade radius, followed by the stop distance and land width. On the other hand, in the case of the trimming load, the blade radius acted as the major parameter, while the influence of the stop distance and land width were insignificant. The shape defects in the final product were minimized when a 0.2 mm blade radius, 1.0 mm land width, and 0.25 mm stop distance were used during trimming. The trimming load was found to be the lowest when a 0.2 mm blade radius, 1.5 mm land width, and 0.75 mm stop distance were used for trimming. The process conditions for the land width and stop distance were determined based on shape defects which exhibit relatively high influence. Therefore, the optimum conditions in the proposed trimming process were a 0.2 mm blade radius, 1.0 mm land width, and 0.25 mm stop distance.

The trimming experiment produced a shear surface with a shape very similar to that predicted using FEA, thereby verifying the validity of the FEA model used in this study. Based on the above results, we expect that the proposed trimming process can be used to trim bolts to specifications other than an M12 bolt.

Acknowledgments

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References

[1] H. S. Choi, S. G. Kim, H. K. Choi, B. M. Kim, and D. C. Ko, “The effect of clearance and inclined angle on sheared edge in trimming of UHSS,” Proceedings of the Korean Society for Technology of Plasticity fall conference, pp. 440-443, 2012 (in Korean).

[2] J. H. Lee, K. H. Lee, and S. B. Lee, “Process design of trimming to improve the sheared-edge of the vehicle door latch based on the FE simulation and the Taguchi method,” Journal of the Korea Academia-Industrial Cooperation Society, vol. 17, no. 11, pp. 483-490, 2016 (in Korean).

[3] M. Li, “An experimental investigation on cut surface and burr in trimming aluminum autobody sheet,” International Journal of Mechanical Sciences, vol. 42, no. 5, pp. 889-906, 2000.

[4] X. Han, K. Yang, Y. Ding, S. Tan, and J. Chen, “Numerical and experimental investigations on mechanical trimming process for hot stamped ultra-high strength parts,” Journal of Materials Processing Technology, vol. 234, pp. 158-168, 2016.

[5] C. MacCormack and J. Monaghan, “A finite element analysis of cold-forging dies using two- and three-dimensional models,” Journal of Materials Processing Technology, vol. 118, no. 1-3, pp. 286-292, 2001.

[6] C. MacCormack and J. Monaghan, “Failure analysis of cold forging dies using FEA,” Journal of Materials Processing Technology, vol. 117, no. 1-2, pp. 209-215, 2001.

[7] K. W. Kim, G. T. Lee, and H. Y. Cho, “A forging die design to improve the flower shape of flange bolt,” Journal of the Korean Society of Marine Engineering, vol. 40, no. 4, pp. 314-319, 2016 (in Korean).

[8] K. W. Kim, Y. G. Qiu, and H. Y. Cho, “Design of eccentric forging process for camber bolts using finite element method,” Journal of the Korean Society of Marine Engineering, vol. 40, no. 4, pp. 320-324, 2016 (in Korean).

[9] H. Y. Cho, W. J. Kim, S. J. Lee, N. K. Park, and S. H. Lee, “Finite element analysis for forging of nonaxisymmetric cam bolt,” Proceedings of the Korean Society of Mechanical Engineers spring conference, pp. 965-970, 2007 (in Korean).

[10] J. Petruska, J. Borkovec, J. Hulka, and R. Foret, “Application of ductile fracture criteria to industrial cutting processes,” Advanced Materials Research, vol. 264-265, pp. 913-918, 2011.

[11] T. S. Kwak, Y. J. Kim, and W. B. Bae, “Finite element analysis on the effect of die clearance on shear planes in fine blanking,” Journal of Materials Processing Technology, vol. 130-131, pp. 462-468, 2002.

[12] S. C. Park, W. R. Dong, and K. H. Lee, “Design of integrated forming process for manufacturing Al6061 alloy bolt,” Proceedings of the Korean Society for Technology of Plasticity fall conference, p. 146, 2017 (in Korean).