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Research Article

Fabrication Improvement of Cold Forging Hexagonal Nuts by Computational Analysis and Experiment Verification

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Cold forging has played a critical role in fasteners and has been applied to the automobile industry, construction industry, aerospace industry, and living products so that cold forging presents the opportunities for manufacturing more products. By using computer simulation, this study attempts to analyze the process of creating machine parts, such as hexagonal nuts. The DEFORM-3D forming software is applied to analyze the process at various stages in the computer simulation, and the compression test is also used for the flow stress equation in order to compare the differences between the experimental results and the equation that is built into the computer simulation software. At the same time, the metallography and hardness of experiments are utilized to understand the cold forging characteristics of hexagonal nuts. The research results would benefit machinery businesses to realize the forging load and forming conditions at various stages before the fastener formation. In addition to planning proper die design and production, the quality of the produced hexagonal nuts would be more stable to promote industrial competitiveness.

1. Introduction

Screws, also called fasteners, are broadly applied and are essential parts. Advanced countries with higher industrialization have higher demand for large quantities of screw fasteners. Fasteners are essential in our daily lives. With the global recession the fastener industry in Taiwan has suffered from major impacts of the emerging countries of Mainland China, Southeast Asia, and India as well as antidumping. More challenges are expected. The forging process in the fastener industry is an important technology. Forging is a processing craft changing the shapes of metal materials with pressure so that the materials become forged with certain mechanical properties, shapes, and sizes. In other words, the metal materials are compressed or extruded between dies in order to increase partial or entire height and width or to change into required shapes. In this case, the quality of forging dies would affect the quality, cost, and efficiency of products. It therefore becomes critical to rapidly design a die and verify the reliability of the die to enhance the industrial value.

Most manufacturers who require mass production of screws would choose cold forging. Cold forging is an ordinary but important metal processing process, mainly utilizing a die to fix the lower part of a metal rod to the required shape with punch. The final products are mainly used for the connection of various construction parts. Since heating is not necessary, the surface precision and smoothness are optimum. At the same time, expensive forging die is preserved for a longer service life. This could reduce the forging cost and the metal strength could also be enhanced. Falk et al. [1] applied the finite element software, DEFORM, in 2001 to propose the forging volume correlated method, which could simply and accurately estimate the cold forging die life but was also verified with experiments. With the ANSYS finite element software, Landre et al. [2] utilized the finite element software for simulating the cylindrical compression process of 1040 carbon steel, discussed the effects of three preforming shapes on the forming limit, and predicted the strain location of blank fracture on the workpiece. Besides, the fracture ratio was used for comparing the process applicability among various criteria. Lee et al. [3] used DEFORM for analyzing the mold stress for cold forging in 2002 and divided it into two procedures. In procedure 1, the mold was assumed to be a rigid body, the load was added on the mold after the blank was being formed, and then the stress analysis was preceded. In procedure 2, the mold was assumed to be an elastic body in the process of blank forming for mold stress analysis. The mold stress with such two procedures was compared with it in the experiment. The result showed that the strain of the mold assumed to be an elastic body was close to the experiment. Hence, the precision of DEFORM is convincible in this study. Tamura et al. [4] examined the dimensional precision and uniformity of forged round billets. In the research, a three-dimensional rigid-plastic finite element method was used and the validity of the analysis was examined by laboratory experiments using lead billets. At the same time, the independent influence of each chosen major operational parameter, that is, the rotational angle and the feed, has been clarified and specified. As a result, the optimum combination of rotational angle and feed had been suggested taking account of not only dimensional precision but also productivity. Joun et al. [5] presented an application-oriented finite-element approach to forging die structural analysis. In their works, the loading condition was extracted automatically from a forging simulator, based on the rigid-viscoplastic finite element method, and preload due to the clamping force was also considered in the same manner. Sofuoglu and Gedikli [6] used physical modeling and ANSYS software for analyzing the internal mesh changes of workpiece and the extrusion load with distinct punch displacement, when the various extrusions rate and die semiextrusion angle were used in the 3D extrusion process. MacCormack and Monaghan [7] acquired Latham's criterion coefficient, analyzed the forming process of hexagonal bolts and the shear load of molds, and improved the forming process to determine the parameters in the forming process in 2001. Furthermore, MacCormack and Monaghan used DEFORM for analyzing the effects of the mold parameters for forming hexagonal bolts on the mold stress. The analysis results showed that the mold stress would be reduced and the service life would be prolonged when the geometric shape of the mold allowed the material to easily flow in the forming process. Kim [8] applied multistage continuous cold forging to form the terminal pin, in 2007, when the extrusion and upsetting replaced the traditional welding, utilized CAMPform-3D and cold forging for the verification, and successfully produced the products, which avoided the 10% defects caused by welding. Wang and Chen [9] solved the problems in the thin-wall parts processing and, with the example of typical axial thin-wall parts, preceded an overall analysis of the processing method in order to find out the feasible processing method for the reference of similar thin-wall parts processing. In order to solve blank defects, waste of raw materials and energy, long processing procedure, and low production efficiency in the production of track end coupling, Ma et al. [10] used the DEFORM-3D software and field small-batch production for proving the advantages of extrusion forming, including high size precision, reduction of production cost, and good formability, to satisfy the demands for mass production.

Incremental forging techniques offer the opportunity to produce accurate ring-type components with smaller loads than pressing operations. Guangchun and Guoqun [11] used a finite element method in analyzing a rotary forging process. A three-dimensional rigid-plastic finite element analysis code was developed in FORTRAN language and used to analyze the rotary forging process of a ring workpiece. The results showed that the mechanical model found in this paper agreed well with the practical rotary forging process. Microforging is an area of great potential, especially in electronic and medical devices; for example, Hsia et al. [12, 13] used the finite element software, DERORM-3D, for simulating the 3C micro pin forward extrusion and forging process in 2013 and 2014. The research simulated the forward microextrusion of blanks and discussed the differences between the simulated stage process and the experimental process. Their research also evaluated the effective stress-strain and material flow properties after the extrusion and the punch head reaction when the predicted material was being formed for the evaluation standard for designing the punch head and the strength of die structure.

The publication of a much wider range of industrial forging applications would greatly encourage the use of computational simulation. Aiming at the formation process of hexagonal nuts, this study attempts to precede software analysis and simulation to discuss the distribution of stress, strain, velocity field, and load at each stage so as to assist the businesses in predicting possible problems in the forming process when designing the dies. Furthermore, the development cost for dies could be reduced to make the fastener production more efficient.

2. Research Methodology and Experimental Framework

In the fastener industry, vast experience with the product is crucial. The lack of powerful support of theories and known science could result in developmental bottlenecks. For instance, products that are constantly tested on the platform could delay the product delivery. The increasing costs would affect the fastener industry. Utilizing the computer aided analysis software, FEM(DEFORM-3D), for metal forging has been important in the past years and has become the developmental trend. Introducing computer aided design and analysis into the design and production of fastener dies could effectively shorten the development time of products further reducing the number of die testing times and avoiding the formation of failures. In addition to ensuring the quality of forgings and enhancing the service life of dies, it could reduce the costs for material usage and die modification.

2.1. Cold Forging Theory. Since metal forming is a complicated deforming behavior, the assumption of boundary conditions and material characteristics in finite element analysis being accurate and reasonable would largely affect the analysis results. In this case, suitable assumptions were required for the simulation when analyzing or simulating the plastic processing so as to reasonably simplify the plastic processing complexity and reduce the algorithm time. The assumptions for the simulation are listed as below.

2.1.1. Yield Criterion. Generally, von Mises yielding criterion is adopted as material plastic rule. It provides the relationship between the material yield condition and 3D stress states. All three axial principal stresses σ_1, σ_2, and σ_3 can be expressed as the effective stress $\overline{\sigma}$ shown in

$$\overline{\sigma} = \frac{1}{\sqrt{2}}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]^{1/2} \quad (1)$$

von Mises pointed out while the effective stress reaches the material's yield strength value Y, then the plastic deformation will begin in this material. Equation (1) is expressed as

$$\overline{\sigma} = \frac{1}{\sqrt{2}}\left[\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2\right]^{1/2} = Y. \quad (2)$$

2.1.2. Constant Temperature Mode. The forming temperature was kept at the room temperature and the temperature resulting from the plastic deformation of forged workpiece metal in the cold forging process was small that the effects of the local temperature were ignored.

2.1.3. Friction Model. The cold forging processing of fasteners revealed high contact pressure that the constant frictional model was utilized for the interface friction; the constant frictional factor was regarded as the interface frictional coefficient and the interface friction between the mold and the work remained constant in the process.

2.2. Experimental Steps. The computer simulation analysis software, SolidWorks, is applied to establish the 3D geometric model of dies and workpieces in this study. Figure 1 shows the 5-stage product of the analyzed hexagonal nut; Figure 2 displays the operation of die, punch pins, and forging workpiece, with 1/6 of the original shape. The first stage is the preformation of hexagonal nut, the second stage is to change the external shape of hexagonal nut, the third stage and the fourth stage reveal large changes on punch pin, which appear to show larger loads because of the hole preformation of hexagonal nut, and the fifth stage follows the processes of the previous two stages and continues the cold forging deformation till the final product size. For the analysis, the figures are first transformed into STL files and then imported into DEFORM-3D forming software for simulation. The analysis flow chart is shown in Figure 3, where the research direction is first determined and then the true materials are acquired for the compression test in order to acquire the flow stress for verification. The simulation analysis at various stages could be preceded when the experimental result is correct. The final results are compared with the field processing in order to verify the feasibility of the entire computer simulation.

2.3. Compression Test. The workpieces proceeded in the compression experiment with a universal testing machine in order to acquire the data of cold forging load and compressing steps, with which the true stress and true strain are calculated, the flow stress line graph is drawn with the Grapher software, and the equation is acquired with statistical regression.

Figure 1: Finished products of the hexagonal nuts.

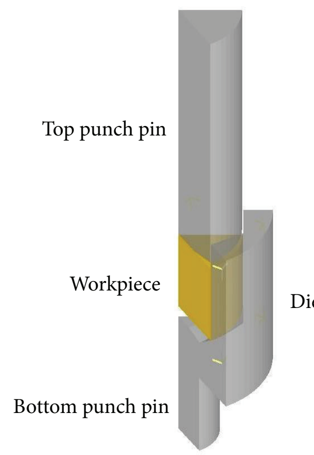


Figure 2: Schematic diagram of the die construction.

In the experiment, the material AISI 1010 is first cut the same as the hexagonal nut for the test cylindrical sample, the external diameter and length ratio is set to be 1 : 1.5, and the actual external diameter of the completed cylindrical sample is 6 mm and the height 9 mm. A universal testing machine with 100 ton pressure is used for the compression test; the cylindrical sample is coated with the lubricant (manganese dioxide) before the compression so that the material could be tested by being closer to the actual production line. After the compression to these reduction from 30%, 60%, 75%, and 90%, Figure 4, the computer would automatically record the cold forging load, compressing step, and deformation time in the experimental process. Such data are further calculated and organized with Excel. The cold forging load, compressing deformation process, and geometric shape of the cylindrical sample are transferred into engineering stress and engineering strain with (3) and (4) and are further transformed into true stress and strain with (5) and (6).

Engineering stress:

$$\sigma_N = \frac{P}{A_i}. \quad (3)$$

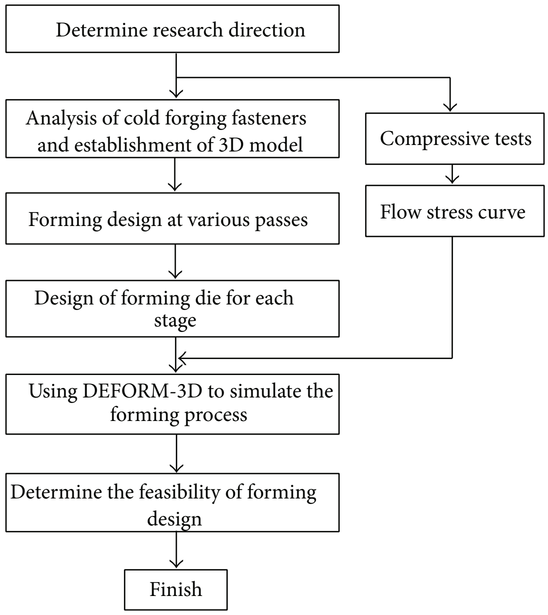


Figure 3: Study of the flowchart.

Figure 4: Compressed cylindrical samples at 30%, 60%, 75%, and 90% reductions.

Engineering strain:

$$\varepsilon_N = \frac{h_i - h_f}{h_f}. \tag{4}$$

True stress:

$$\sigma_t = \sigma_N (1 - r). \tag{5}$$

True strain:

$$\varepsilon_t = -\ln (1 - r), \tag{6}$$

where P is compressing load, A_i and h_i are initial cross-section area and height, h_f is height at the deformation, and $r = (h_i - h_f)/h_i$ is reduction. In the compression test, the engineering strain and the reduction are equal; that is, $\varepsilon_N = r$.

Having acquired the true stress and true strain with the above equations, they are added in the Excel software and calculated the flow stress curve with Power Law, Figure 5, and the flow stress equation $\sigma = 633.63\varepsilon^{0.13}$, where the constant 633.63 is the strength coefficient and 0.13 is the hardening index. In this compressing test, the initial height h_i of the cylindrical sample is 9 mm and the diameter d_i is 6 mm. The maximum reduction 90% shown in Figure 4 means true strain 2.3 mm/mm, but only up to the amount of 1.5 mm/mm

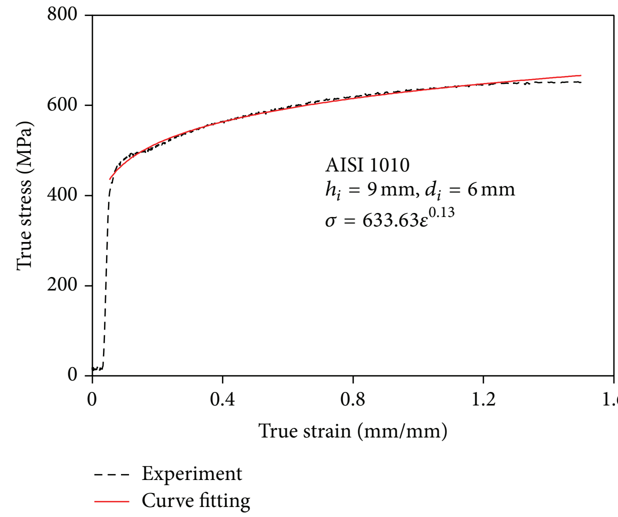


Figure 5: True stress and true strain curve for AISI 1010.

Table 1: Parameter of setting in software.

Workpiece	AISI 1010
Flow stress	$\sigma = 633.63\varepsilon^{0.13}$
Friction factor	$m = 0.12$
Axially symmetric structure	1/6
Mesh number	30000
Punch speed (mm/sec)	420
Forward volume of one step (mm)	0.02
Workpiece/die	Rigidity plastic/rigidity

is widely used to obtain flow stress data for metal forming applications. Having acquired the flow stress, the equation is further substituted in DEFORM-3D for the simulation, which is compared with the analysis result with the equation built in the software database in order to understand the difference in the computer simulation result between the actual compression test and the software at various stages for future reference.

2.4. Selection of Simulation Parameter. The die, deformation materials, and simulation parameters for settings in the analysis process are shown in Table 1. In the preforming operations, a friction factor of 0.12 is applied to model the cold forging conditions because of the lubricated conditions between the forging die and workpiece. Inputting the above parameters to the computer simulation software, DEFORM-3D, could proceed the analysis at various stages. Since the load on materials would directly affect the material life, the load acquired from the experiment and the flow stress curve simulation built in the analysis software are compared and discussed.

3. Result and Discussion

3.1. Cold Forging Loads from Database and Compression Test. The 5-stage process of hexagonal nuts with the database built

Table 2: Cold forging loads for database and compression experiment.

1/6 Axially symmetric	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Stroke (mm)	1.24	3.24	5.3	7.16	9.46
Load (kN)					
Database	12.92	31.01	40.99	40.39	19.26
Experiment	13.36	29.68	36.34	39.61	19.55
Difference between database and experiment	+0.436	−1.333	−4.652	−0.778	+0.289
Percentage of difference (%)	+3%	−4%	−11%	−2%	+2%

in the computer simulation and the flow stress curve acquired with actual compression test proceeded with simulation and analysis, Table 2. The basis of reference of cold forging load is acquired from the database in the computer simulation software, and plus-minus signs are used for presenting the difference from the simulation result with the actual compression experiment. A plus sign stands for the result larger than the database, while a minus sign presents the negative. The load in Table 2 is the final compressing step at each stage; and, 1/6 symmetric hexagonal nuts are meshed for the simulation analysis that the real cold forging load is the final load multiplied by 6. With the comparison, the larger difference 11% appears at the third stage, while the error at other stages is revealed to be between 2% and 3%. In the 5-stage simulation result, Figure 6, the red line is the simulation result based on the flow stress curve in the database, the black line is the simulation result of the flow stress curve in the compressing experiment, and the blue one is the difference between the two. In the comparison, the largest difference appears on the beginning of compression at each stage, where the largest 80% among the 5 stages appears on the compressing step 0.04 mm at the third stage. In this case, the largest difference would appear in the interval when the material starts to flow, that is, the first few steps after the beginning of the compression, in regard to flow equations for the simulation analysis with the DEFORM-3D forming software either with the compression experiment or the database built in the software. The simulation analysis then follows the true stress and true strain relationship in the flow equation $\sigma = 633.63\varepsilon^{0.13}$. Figure 6 also presents the cold forging load 80.16 kN (10%) at the first stage, 178.08 kN (21%) at the second stage, 218.04 kN (26%) at the third stage, 237.66 kN (about 29%) at the fourth stage, and 117.3 kN (14%) at the fifth stage, with the total load 831.24 kN.

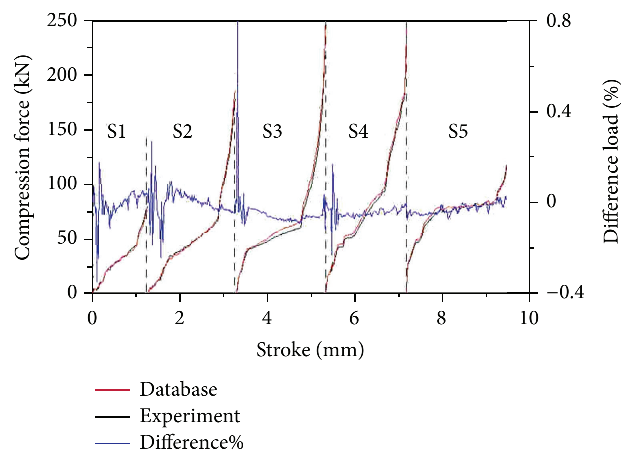
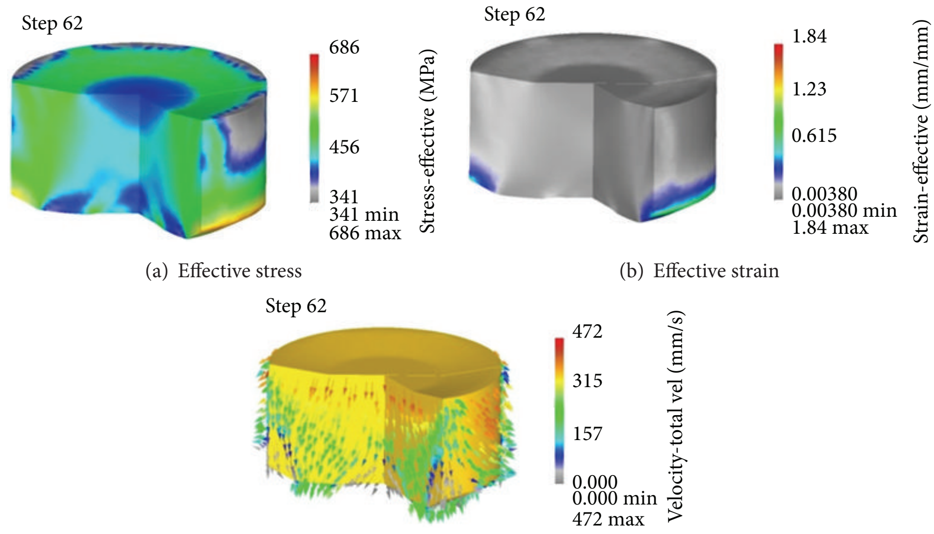


Figure 6: Relationship of load-stroke in five stages.

3.2. Simulation Analysis of Hexagonal Nuts Process. The simulation result at 5 stages with the computer simulation software, DEFORM-3D, the effective stress, effective strain, and velocity field at each stage could be recorded. Figures 7–11 show the analysis results from the first stage to the fifth stage. Since stress would affect the material life and the forming process and result, higher stress presents a higher hardening index that the material might not be easily processed. Besides, stress would focus on corners in general processing that the die should be designed to be rounded for the smooth flow of materials. Strain could assist in understanding the deformation location in the formation, and velocity field helps us understand the flow of materials in the cavity in the compression process.

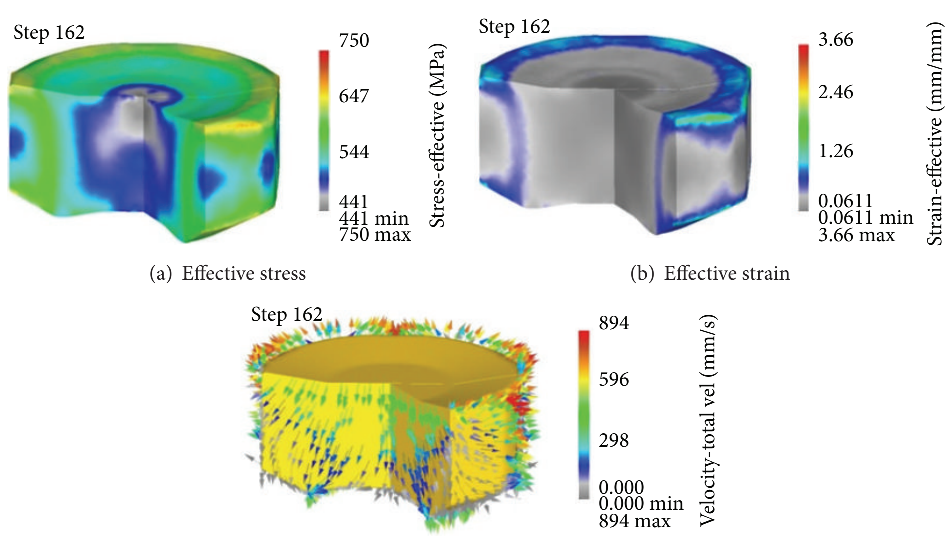
Figure 7 shows the preformation at the first stage, where the maximal effective stress 686 MPa and the maximal effective strain 1.84 mm/mm appear on the internal bend angle of the die and the fastest velocity of the velocity field 472 mm/sec appears on the head. Figure 8 shows the maximal stress 750 MPa and the maximal strain 3.66 mm/mm at the second stage on the external bend angles of the upper and lower parts and the maximal velocity 894 mm/sec. As the figure of the top punch pin reveals obvious changes at the third stage, Figure 9, the stress focuses on the pin extrusion surface on the top surface and the bottom surface, and the maximal stress 761 Ma, the maximal strain 4.10 mm/mm, and the velocity field 1750 mm/sec appear on the periphery of the material top surface. Figure 10 shows the maximal stress 814 MPa and the maximal strain 6.85 mm/mm at the fourth stage, where the bottom formation presents larger changes, and also the maximal velocity field 1920 mm/sec on the periphery of the top surface. Figure 11 shows the fifth forming stage, where the maximal stress 922 MPa and the maximal strain 17.9 mm/mm appear at the material inside hole, the overall stress and strain distribution reveals even more than the first four stages, the maximal velocity field reveals 1190 mm/sec, and the flow appears on the bottom surface and the top surface. Figure 12 displays the analysis results at the extra stage, where the maximal effective stress 839 MPa occurs at step 165, concentrating on the area where the remainder is cut; the maximal effective strain 8.65 appears on the same position



(a) Effective stress (b) Effective strain

(c) Velocity

FIGURE 7: Effective stress, effective strain, and velocity of first stage in 3D.



(a) Effective stress (b) Effective strain

(c) Velocity

FIGURE 8: Effective stress, effective strain, and velocity of second stage in 3D.

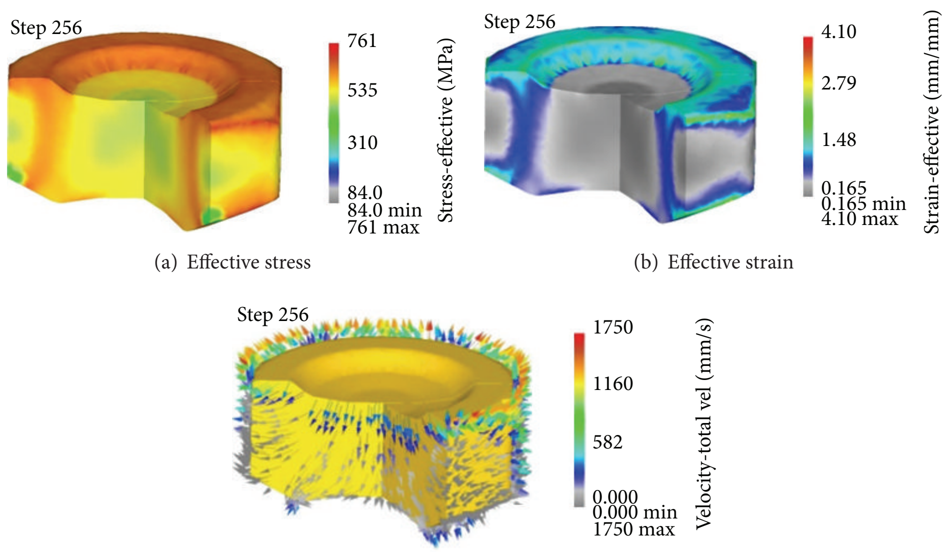
as the maximal effective stress; and the maximal velocity field 431 mm/sec appears on the bottom area after cutting the hole flat. From the above simulation results, the hexagonal nut shape shows the greatest change at the fifth stage that the maximal effective stress and effective strain occur at the stage, and the maximal velocity field appears on the fourth stage.

Table 3 indicated the comparison of the simulative and experimental dimensions on the different stages of the cold forging hexagonal nut. Only the sizes of the diagonal and thickness are discussed in this study. Because 1/6 symmetric mesh is set in the simulation, the dimensions of y-axis indicate diagonal and z-axis mean thickness. The simulative results are obtained from the analysis of DEFORM-3D, and experimental dimensions of the different forging sequences from a workpiece metal to the finishing stage are measured as shown in Figure 1. From Table 3, the percentages of error are no more than 6.6%, for example, the maximum on the diagonal dimension of the first stage.

3.3. Cold Forging Characteristics of Actual Forging Parts. To understand the correctness of the previous simulation of cold forging hexagonal nuts, the analysis results are preceded by the die design and then the cold forged hexagonal nuts tested the hardness and metallography in order to confirm the effects of stress, strain, and velocity field on the formed hexagonal nuts for future modification. In this study, the effects on the most important mechanical property, hardness,

Table 3: Comparison of the dimension between the simulation and actual forging parts.

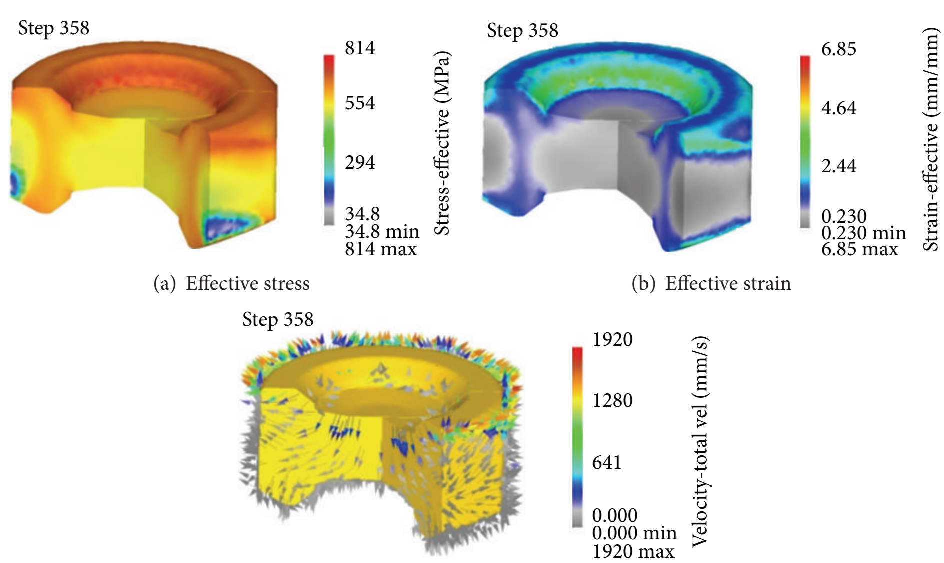
Stage	First stage		Second stage		Third stage		Fourth stage		Fifth stage	
Dimension	Diagonal	Thickness	Diagonal	Thickness	Diagonal	Thickness	Diagonal	Thickness	Diagonal	Thickness
Specification	—	—	—	—	—	—	—	—	14.38 Min.	6.14/6.50
Simulation (mm)	12.89	6.69	13.90	6.42	14.33	6.41	14.33	6.41	14.79	6.67
Experiment (mm)	13.80	6.58	13.68	6.06	14.15	6.09	14.40	6.28	14.62	6.38
Error (%)	−6.6	1.7	1.6	5.9	1.3	5.3	−0.5	2.1	1.2	4.5



(a) Effective stress (b) Effective strain

(c) Velocity

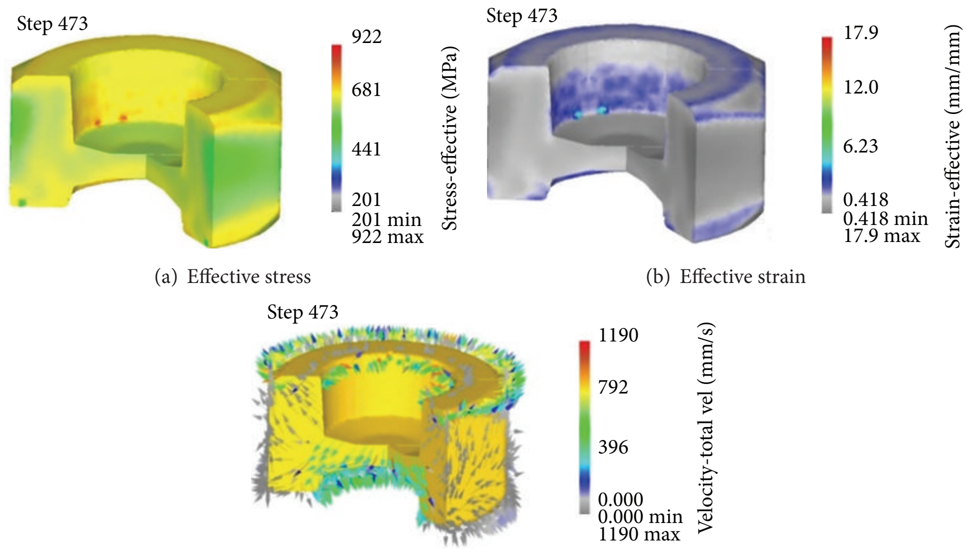
Figure 9: Effective stress, effective strain, and velocity of third stage in 3D.



(a) Effective stress (b) Effective strain

(c) Velocity

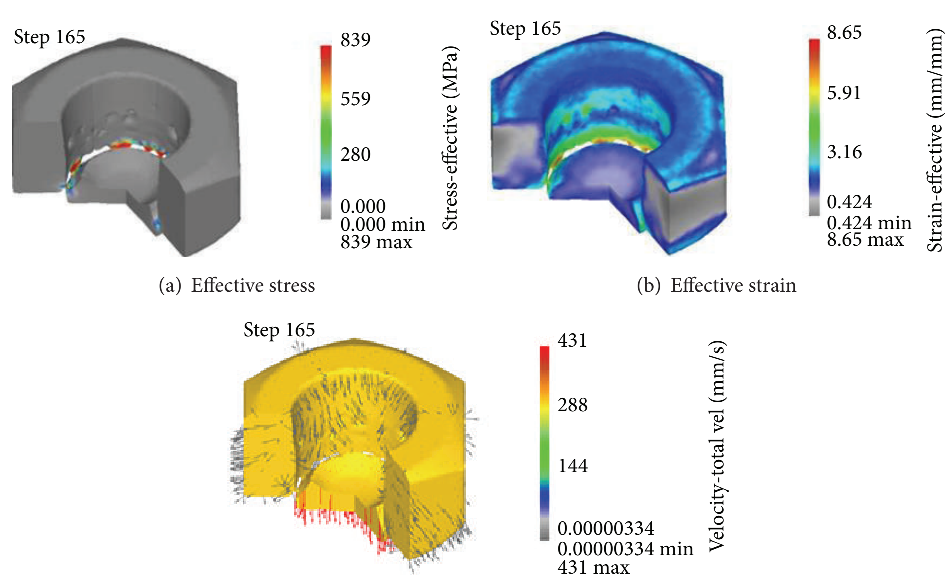
Figure 10: Effective stress, effective strain, and velocity of fourth stage in 3D.



(a) Effective stress (b) Effective strain

(c) Velocity

Figure 11: Effective stress, effective strain, and velocity of fifth stage in 3D.



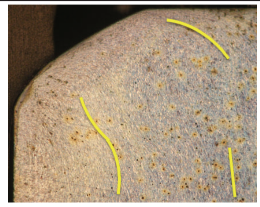
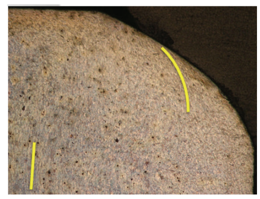
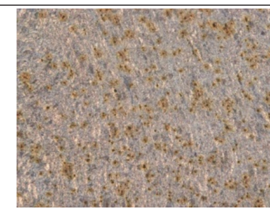
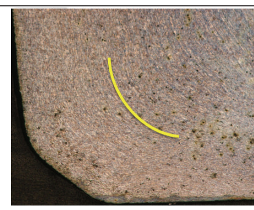
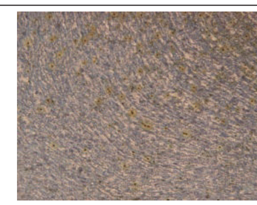
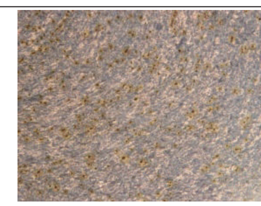
(a) Effective stress (b) Effective strain

(c) Velocity

Figure 12: Effective stress, effective strain, and velocity of sixth stage in 3D.

at various stages in the cold forging process could be acquired with Vickers hardness test, where the pressing load is 100 g. Figure 13 shows 9 measuring points taken from the hexagonal nut section; Figure 14 displays the curve diagram of the hardness measured in Vickers hardness test. The order of the test points in Figure 13 starts from the upper inner side of the hexagonal nut and then moves along the outer side for the measurement; the last 2 measuring points are located on the center. From Figure 14, the hexagonal nut inner side, going through multipass processing for the via hole formation, would appear to have a higher hardness than the outer side; for example, points 1, 7, and 8 present the highest hardness. The hexagonal nut outer side deforms merely because of the upper punch cold forging extrusion at first stage that the hardness is lower than it of the inner side; for example, points 3, 4, 5, and 6 reveal lower hardness. Generally speaking, the larger deformation requires more processing times that the hardness is relatively higher. Figure 15 displays the distribution of the maximum principal stresses in the third, fourth, and fifth stages of the cold forging sequence. Due to the large deformation occurring in the workpiece, the FEM mesh degenerates severely during simulation. Consequently, remesh procedure is carried out frequently to complete the simulation. Figure 15 also indicates the maximum principal

Table 4: Samples of microstructure of deformed hexagonal nut.

Scale factor	50x	100x
On the top left corner		
On the top right corner		
On the bottom left corner		
On the bottom right corner		

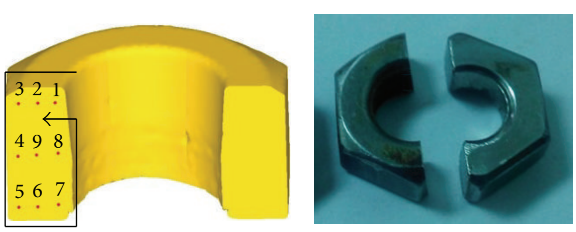


Figure 13: Half workpieces of simulation and experiment.

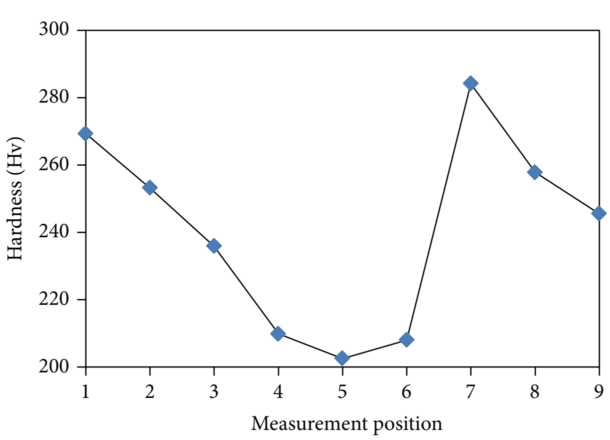


Figure 14: Distributions of hardness in the hexagonal nut.

stresses shown on the inner sides to be in the range 330–1,670 MPa. They are larger than the outer sides of the three stages. Hence, it is clear that high stresses caused by large deformation are concentrated in the inner sides. This cold forging process would induce the hardening phenomena in this region shown in Figure 14.

One of the most important pieces of information in forged product is the metal flow lines. In forging process design, design failures do sometimes occur due to defectiveness in internal metal flow lines even though the outward appearance is successfully shaped. This study also verifies the flow behavior of the hexagonal nuts using the experimental method and numerical simulation. The analyzed hexagonal nuts are small in size that mounting for the metallography is first preceded for the required test chip and then rough and fine grinding and polishing. During rough grinding and fine grinding, the force and the angle have to be stable, and the test chip continues the grinding after being rotated 90°C every certain time. Such actions are cycled till the surface scratches disappear. Aluminum oxide, with the size 0.3 μm and about 3-4 drops, is the grinding material used in the test process and it should be immediately dried and corroded after the polishing in order to avoid the oxidation on the test chip surface influencing the quality of metallographic observation. Table 4 shows the metallographic location of hexagonal nuts with via hole and the flow line distribution. In Table 4, the microstructure of the left right corner is about

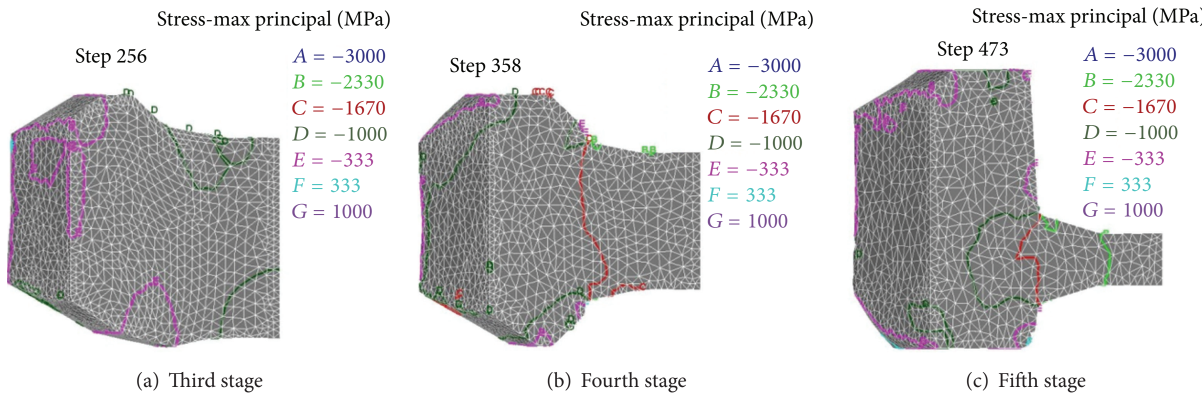


Figure 15: Maximum principal stresses of the third, fourth, and fifth stages in the hexagonal nuts.

formed in the previous 3 stages, as the little deformation has the metallography not appear obvious direction; the microstructure of the top right corner is the inner wall of the via hole, with obvious downward flow line; the flow line at the bottom left corner could be referred to as the velocity fields at the first and the second stages, presenting counterclockwise flow; and, the flow line at the bottom right corner could be referred to as the velocity field of the fifth stage, revealing clockwise flow. According to Table 4 and Figures 7–11, the velocity fields of hexagonal nuts simulated at various stages could be used for explaining the material flow caused in the forming process. Such information could be the specific reference for die design and modification.

4. Conclusion

The analysis with the computer simulation software, DEFORM-3D, allows for understanding of the forming process of hexagonal nuts, which could be the reference of future product design or improvement. The research findings are summarized below.

(1) The maximal load 237.66 kN appears at the fourth stage, about 29% of the entire cold forging process, and followed by 218.04 kN at the third stage, about 26%, in the 5-stage hexagonal nut processing. Hence, the changes of top punch pin and the increase of formation quantity would result in the rapid increase of load.

(2) The major stress in the 5-stage forming focuses on the contact between the die bend angle and the pin, and an evener distribution of stress does not appear till the fifth stage.

(3) According to the metallographic test results, the flow line simulated with software is consistent with the one in the experiment.

(4) In regard to the hardness distribution of hexagonal nuts, the maximal hardness is related to multipass cold forging processing, which mainly focuses on the inner side of a formed hexagonal nut. In this case, the strength required for the upper punch and the impaired service life caused by wearing should be concerned when designing a die.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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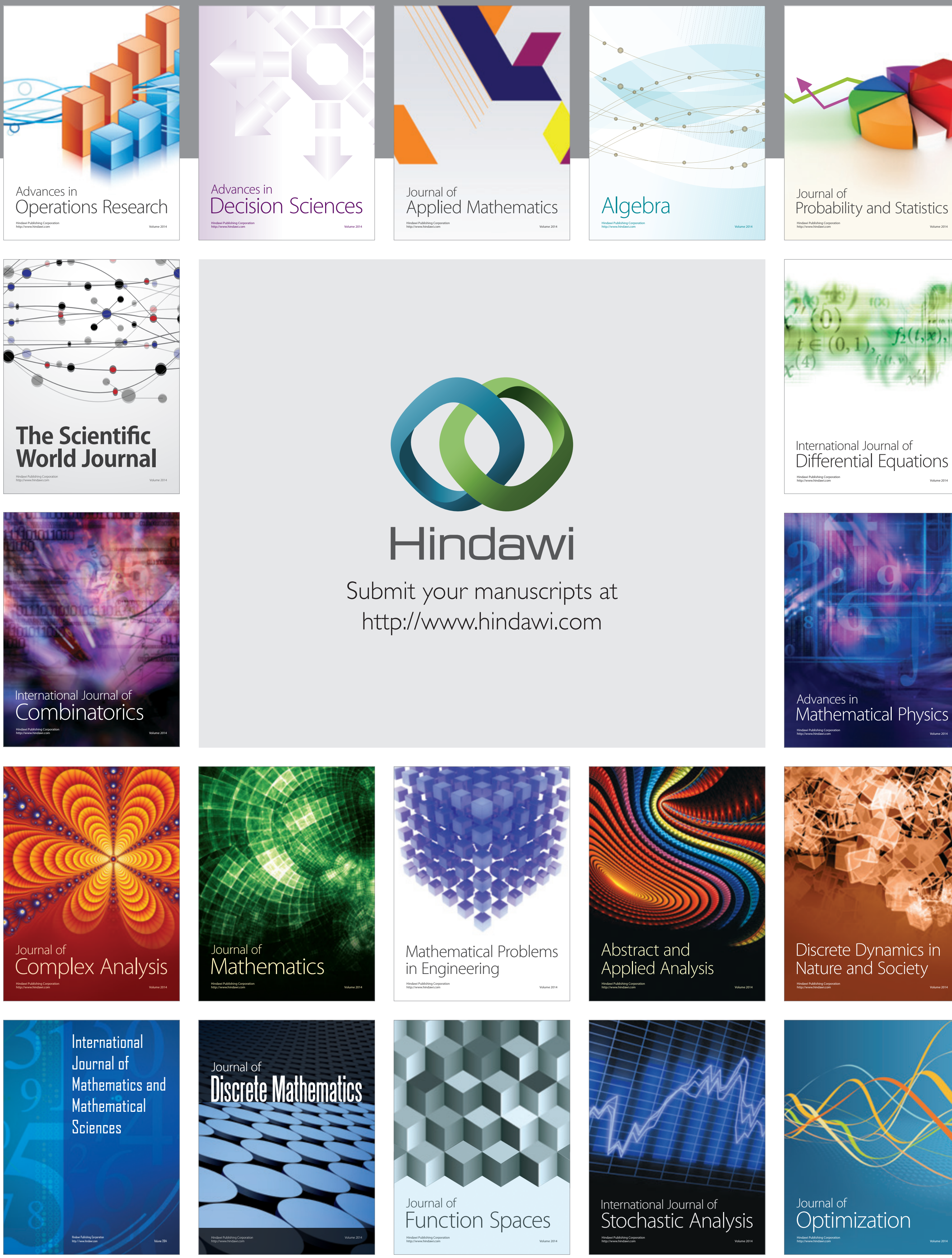
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