Celal Bayar University Journal of Science

Investigation of the cold forging operation steps' effect on forming properties

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Received: 30 November 2020
Accepted: 20 December 2020
DOI: 10.18466/cbayarfbe.833596

Abstract

Cold forming is a manufacturing process that plastically deforms metal using dies. It allows for high speed production, little to no material waste compared to conventional machining, and creates a stronger end product due to work hardening of the material. Cold working in forging process refers to the process of strengthening steel alloy by changing its shape without the use of heat. Subjecting the alloy to this mechanical stress causes a permanent change to the metal's crystalline structure, causing an increase in strength. At this time applied deformation rate, velocity and die design of product effect the mechanical features, flow-orientation properties of sample and load requirements for forging process of rivets. In this study, it is aimed to investigate the operation steps effect on formability characteristics of rivet produced by cold forming with the support of finite element method. Effective plastic strain, yield stress and forging force variations depending on die design were obtained by simufact.forming simulation software. Simulations made with different die designs and physical production results of these dies were compared. The effects of the number of forming operations and die cavity on the process were determined by performing material flow, hardness and structural analysis.

Keywords: Cold Forming, Finite Element Analysis Method, Plastic Forming, Rivet,

1. Introduction

A method of forming a solid body into a different shape without changing the mass and volume of it is called plastic forming method. Ferrous materials such as carbon and alloy steels (including stainless and heat resistant steels), aluminum, zinc, copper and their alloys can be processed by plastic forming methods. The most important application areas of the parts produced by these methods can be listed as follows: i) Numerous parts produced for various industries such as automotive, machine tools (car body, crankshafts), ii) Hand tools such as pliers, hammers, screwdrivers and medical tools, iii) Fasteners such as screws, nuts, bolts, rivets and iv) Fasteners used in construction industry, eg using at doors and windows [1].

It is important to know the plastic deformation ability of material, the pressure, strength and power levels required for the process so that the solid metal can be shaped without breakage and separation. For the success of the method, selection of material properties, die design and process parameters are very important [2].

"Cold forging" or "cold forming" is a plastic forming method which is shaped by pressing the workpiece into a die set. The cold forging uses the plastic properties of the metal to shape the metal at room temperature. The production of a part by cold forming instead of machining provides advantages such as material gain, increased mechanical properties due to cold forming, controlled material flow [3].

While designing this process, it is the design advantages gained by using simulation and artificial neural networks model by analyzing multistep cold forming processes based on predetermined process status parameters and tool geometry [4,5]. Finite element methods (FEM) provided a new perspective on metal forming applications in the 1970s and early 1980s. One of these methods, the computer program Battelle Columbus Laboratories, was developed in the US [6]. The first study that led to this development was supported by the US Air Force and was derived from pioneering studies of rigid-plastic FEM conducted by Kobayashi et al [7]. Kim Hyunkee and Taylan Altan in

their study in 1996, contains information about the cold forged parts in the literature and about the forging industry [5]. K.Wagner, A.Putz and U.Engel in their study in 2006, finite element analysis method was used to determine the regions where the deformations of the dies were most concentrated. In order to increase the die life, three different die surface treatment methods were evaluated [8]. In 1992, M.Geiger, M. Hansel and T.Rebhan, the finite element method was used to determine the fatigue resistance of an extrusion die used in the cold forging process [9]. In addition to die analysis with simulation programs, Conor MacCormack and John Monaghan, in 2002, the accuracy of the design of the products can be simulated in 2D and 3D [10]. During the development of metal forming methods and the parameters to be examined during production, the production methods are compared and the processes that have been studied up to date have been evaluated [11].
Analytical results herein demonstrate that the stress and strain inside the rivet can be elucidated using metal forming software. Together with experimental results, they demonstrate that a concentration of stress, strain, flow, yield stress variate the parameter in the forming process. Planning for proper die design and production, increasing the quality of products, and reducing the number of defective products promote industrial competitiveness. Applying the FEM to analyze metal processing presents the advantages of (1) being able to acquire detailed data (e.g. velocity field, geometric shape, effective strain, effective stress, temperature change or contact pressure, and displacement distribution) after object deformation and (2) requiring little programming content and input data when analyzing several relevant problems in rapid solution environments. The % cold forming amount and the number of cold forging operations affect the mechanical properties and forming capability of the material.Forming processes were analyzed considering two different die designs and number of operations by FEM [11-17].

However, with increasing global competition, conventional cold forging processes are facing challenges. This is due largely to the demand from customers who require components with high-precision and a stable quality, using high strength-to-weight ratio materials. On the other hand, industry also needs to reduce cost and improve efficiency against other competitors. As one of the efforts to meet these requirements, cold forging is being researched as a new option from which rivet components can be obtained in a minimum number of forging steps. In this paper, the finite element method was used to analyze the influence of die shapes with different operation number and machine on the extrusion forging deformation. Experiments using two sets of dies with different shapes were performed, and the results were compared with the predictions of the finite element method for the same deformation mode. Thus, the results of the deformation analysis in this study were extended to the design of decreasing operation number or step and in the planning of a forming process. This would be beneficial for the forging industry [15-22].

2. Materials and Methods

The raw material selection of the product is made using EN 10263-4, which is the raw material standard which contains plastic formable, malleable and heat-treated steel. The standard and actual chemical composition of the 20MnB4 raw material to be used is given in Table 1.

Table 1. Comparison of raw material chemical composition according to EN 10263-4.

Elements	Standard variation ranges	Chemical Analysis
C	018-0,23	0,20
Si (max)	0,30	0,09
Mn	0,90-1,20	0,97
P (max)	0,025	0,006
S (max)	0,025	0,008
Cr (max)	0,30	0,2
Cu (max)	0,25	0,04
B (max)	0,0008- 0,005	0,0035

2.1. Die Design Study

Two different processes were designed to examine the effect of the number of deformation steps on cold forming properties. In the first design, which has been designed by considering the cold forging capability and the transitions between the operations, special rivet products are designed as three stations such as; extrusion, forming and heading, in multi-station machines. The product dimensions foreseen by the design are as in Figure 1.

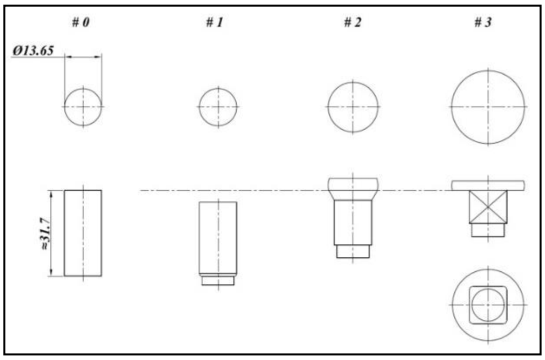


Figure 1. First design: 3 operation.

The existing design, illustrated in Fig.1, was revised. In this revision, it is planned to remove the head preparation performed in the second operation step. As a result of the decrease in the number of stations, the multi-station press machine, where the production of special rivets was made, was replaced and the two die four blow rivet machine was used. In this way, it is aimed to increase the production cycle of the product. The operation card formed after the revised design is as shown in Figure 2.

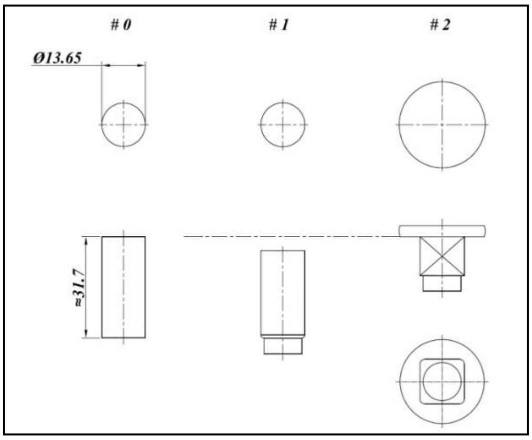


Figure 2. Two operation product design.

2.2. Simulation Study

Numerical simulation using the upper-bound or finite element method is often used in the approach to such research. The different properties and geometry of work piece, the condition and the factor of friction, and the geometry profile of the die were the main objectives of analysis. The deformation behaviour, the flow modes, the deformation load and the filling of the die cavity of the deformed shape were the features of interest in this study. 3D solid models of the dies used in three and two station systems were prepared for simulation solution. Machine parameters, material data, friction model and ambient temperatures defined in the simulation program. Additionally, two different machine features for the production of the part are shown in Figure 3.

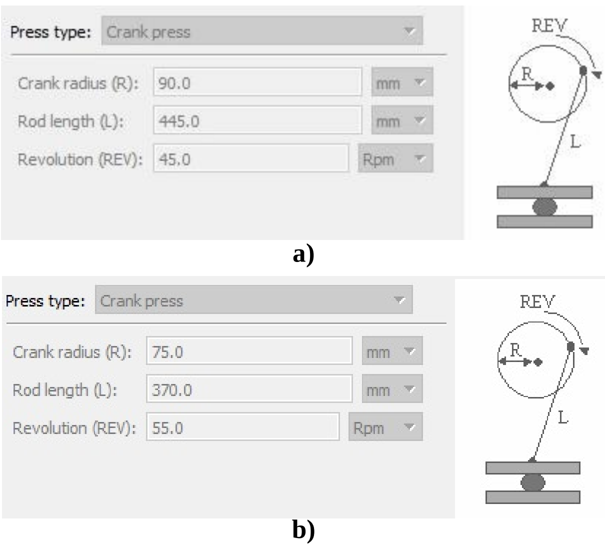


Figure 3. a. Multi station cold forming machine parameters for three station production design and b. Two die four blow cold forming machine parameters.

Due to the lack of raw material data of 20MnB4 in the simulation program, 19MnB4 material which is equivalent to this material has been selected. The material data of 19MnB4 is shown in Figure 4.

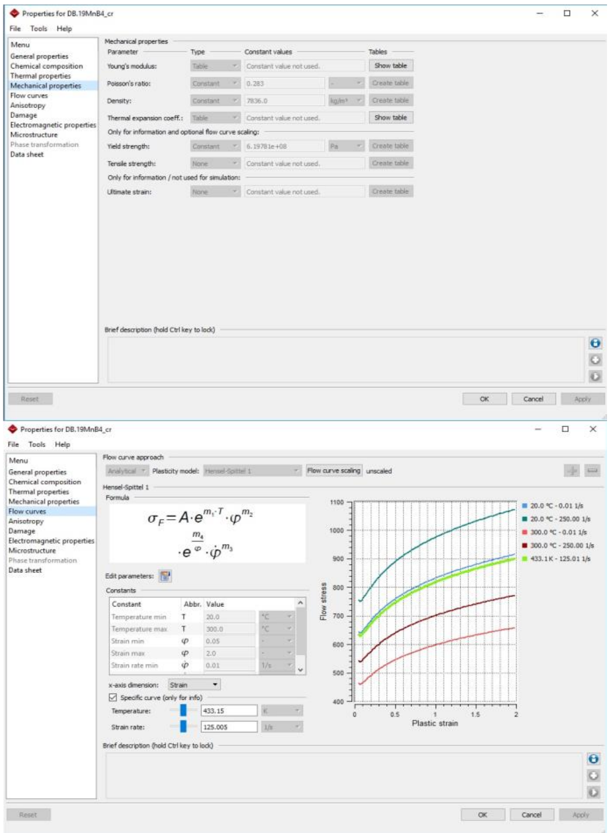


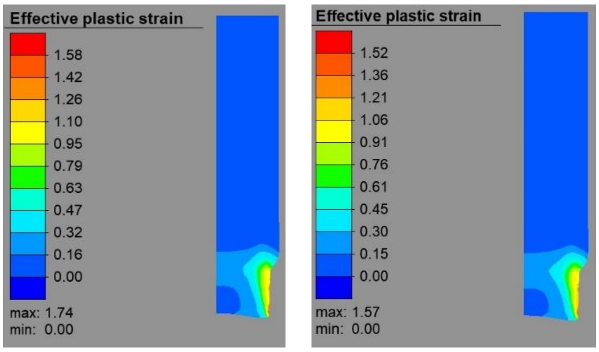
Figure 4. 19MnB4 material data.

The key item of every forming process is the workpiece. Its inherent properties (mechanical, thermal) are defined by the associated material data. Especially the mechanical material properties can be quite complex and are a source of nonlinearity which results in significant computational efforts. As seen in figure 4, in pre-processing stage of analysis analytical flow curve approach with Hensel-spittel plasticity model was used in numerical solution of two and three station production design. The Coulomb model, which is most suitable for the cold forging process, has been chosen as the friction model. The temperature values at which the cold forging process was carried out were taken at ambient temperature 20 °C. At the end of the pre-processing of design; application module and process type, positions and geometries, desired material, press (machine), friction properties, heat properties and workpiece mesh were chosen.

3. Results and Discussion

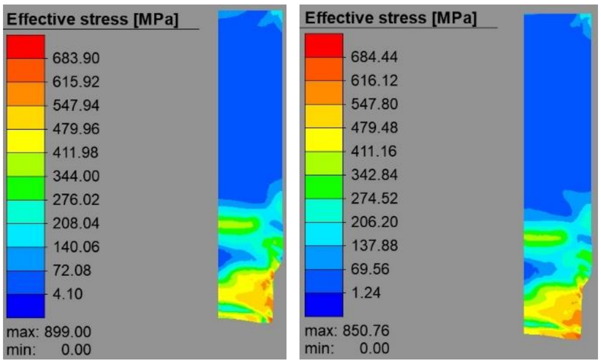
3.1. Simulation Results

In both cases, plastic deformation, stress, yield stress, force values obtained as a result of simulation are as shown in the figures below. The value of effective plastic strain is the integral of stepwise increments of plastic deformation for a period of analysis time t. According to the numerical solution of two ad three station analysis, effective plastic strain distribution is illustrated in Fig. 5 and 6. Effective plastic strain and stress occurs near cold extrusion and reduction of area in die.



a) **b)**

Figure 5. a. and b. Effective plastic strain distributions of the first operating step of the three-station design and the two-station design, respectively.

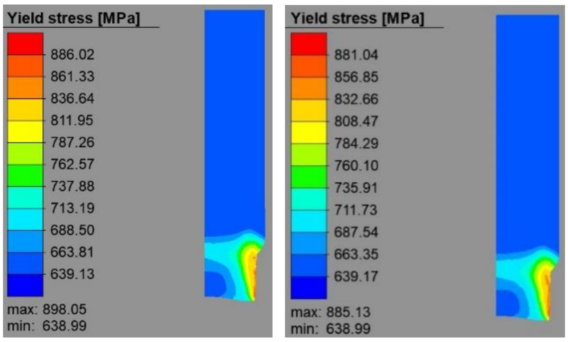


a) **b)**

Figure 6. a. and b. Effective stress distributions of the first operating step of the three-station design and the two-station design, respectively.

The change in yield strength depending on the deformation rate is shown in Figure 7. The yield strength of the material increased from 638.99 to near 890 MPa, where deformation occurred.

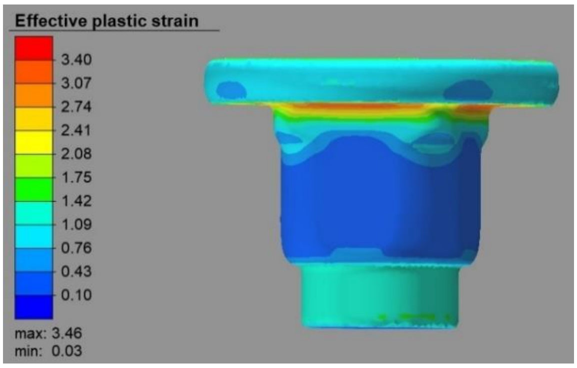
The change in effective plastic strain and yield strength in the final operations of two and three station die designs is shown in Figure 8 and 9. Cold working generally results in a higher yield strength as a result of the increased number of dislocations and the Hall–Petch effect of the sub-grains, and a decrease in ductility, as microstructural explanation. Fig. 5 and Fig. 6 shows cold work effect on work piece.



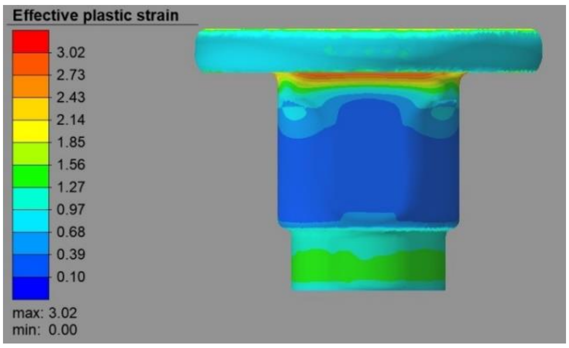
a) **b)**

Figure 7. a. and b. Yield stress variations depending on plastic deformation of sample in first operating step of the three-station design and the two-station design, respectively.

As stated at the beginning of the study, the second operation of the three-station design has been removed. Therefore, the excessive yield strength and hardness increase or material flow-orientation that may occur in the material have been investigated. Since the total deformation did not change, a very high change in yield strength was not observed. In this context, the biggest difference detected was revealed in the deformation load as illustrated Table 2.



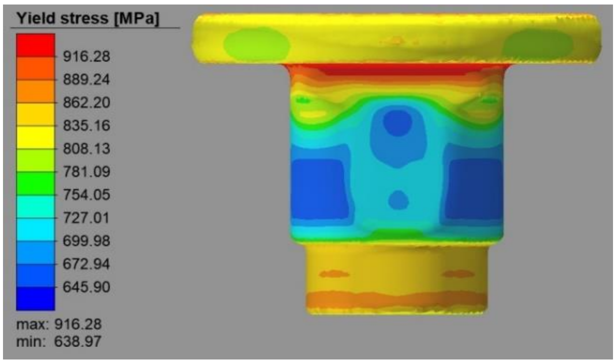
a)



b)

Figure 8. a. and b. Effective plastic strain distributions of the last operating step of the three-station design and the two-station design, respectively.

Celal Bayar University Journal of Science
Volume 16, Issue 4, 2020, p 437-443
Doi: 10.18466/cbayarfbe.833596



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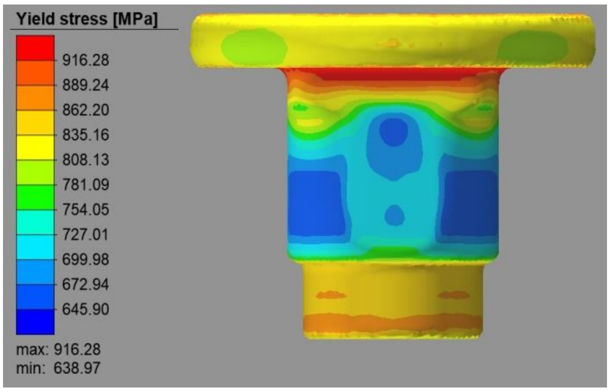


b)

Figure 9. a. and b. Yield stress variations depending on plastic deformation of sample in last operating step of the three-station design and two-station design, respectively.

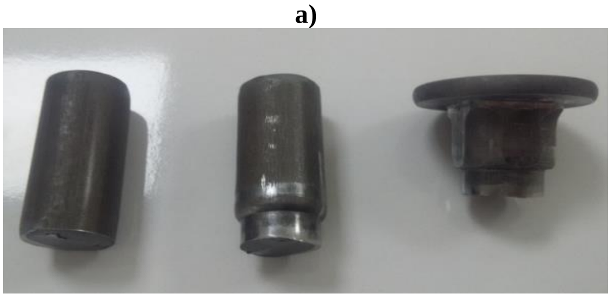
Table 2. Total deformation load of the three-station design and two-station design.

	Three operation design force (ton)	Two operation design force (ton)
First Operation	10.19	10.24
Second Operation	13.72	-
Last Operation	65.9	63.74
Total	89.81	73.98

3.2. Physical Production Results of Different Design

After numerical analysis of the three-station and two-station design of sample were finished, physical rivets were produced as in Figure 10. It has been determined that absence of the second operation step in three operation step design does not affect the final product in dimensions.

a)



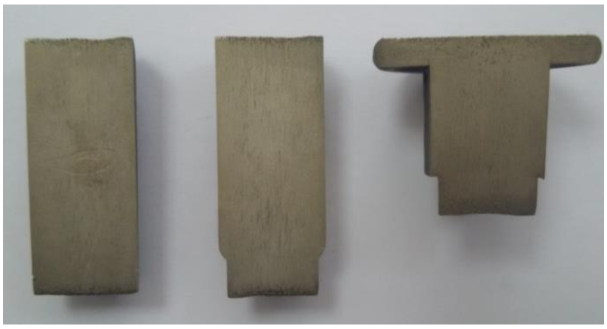
b)

Figure 10. Prototype production of a) three-station and b) two-station design of sample.

3.3. Macro Etching Examination

In order to reveal plastic deformation grain structure in the material, macro etching process was applied to the produced rivets. This procedure was applied to each operation sample of the part produced in three operation steps and the part produced in two operation steps. Macro etching results are shown in Figure 11. When the material flow lines are examined, no discontinuity is observed. Material flow was stable and regular. As a result of the removal of the second operation, no negativity was observed in the rivet section, which is the final product, due to the high shaping and plastic behaviour of the raw material.

a)

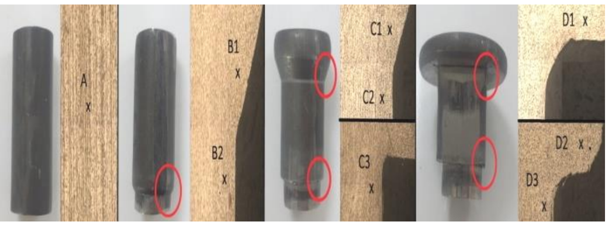


b)

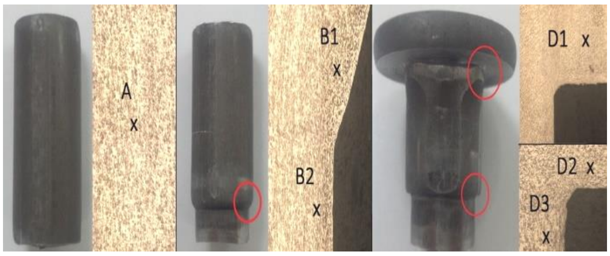
Figure 11. Flow lines of rivets: a) three-station and b) two station design.

3.4. Metallographic Review

Metallographic analysis was performed to examine the microstructural properties of the material. By focusing on the critical cross-sectional change regions of the special rivet, high surface area images have been obtained. The microstructure of the same samples produced by three and two stations design are illustrated in Figure 12.a and b, respectively. The microstructures are oriented without breaking, in the direction of the forging. As a result of plastic forming microstructures of two and three station samples show similar characteristics.



a)



b)

Figure 12. The microstructure (100X) of the same samples produced by a) three and b) two stations forging design**.**

3.5. Micro Hardness Review

Hardness measurements were taken from regions where the cross-section changes during plastic deformation. The hardness changes taken from the places expressed in the microstructure images; figure 12 and b., are shown in Table 3.

Table 3. Hardness measurement of rivets.

Measurement Point	Hardness of three operation design (HV1)	Hardness of two operation design (HV1)
A	196 ±2	202 ± 2
B1	197 ± 1	207 ± 3
B2	200 ± 1	222 ± 2
C1	261 ± 2	-
C2	193 ± 2	-
C3	202 ± 2	-
D1	288 ± 1	282 ± 2
D2	217 ± 2	208 ± 1
D3	216 ± 3	214 ± 2

Table 3 shows the hardness measurements taken from peer stations. Despite the decrease in the number of stations, the hardness in the same area is at the same level. As known, Hardness as a measure of material's resistance to permanent deformation, and thus to wear, is an important quality parameter for the finished product. It is also a measure of forgeability of a material undergoing a cold forming process. Generally, cold formed parts are forged in a number of stages and in each stage the material undergoes additional permanent deformation. The material, during the processing, sometimes becomes so hard that further forming becomes impossible without fracturing the part. When the steel quality used in this study is examined, the amount of hardening by deformation is lower than other grades. However, the change in hardness is noticeable in areas where deformation occurs intensely and material flow is accelerated.

4. Conclusion

Special form rivets were produced in a multi-stage cold forging machine in three operation steps. In the part design, the head preparation process in the second operation was removed and the design was revised. In the new design production, the number of pieces produced per minute increased by approximately 20 %. 13.72 tons needed in the second operation in the three-operation design was eliminated. This resulted in an increase in energy efficiency.

It was investigated whether the decreasing in the operation step caused differences in the microstructure on the part. In this context, microstructure tests, macro etching process and surface hardness screening were performed.

In the microstructure and macro etching test, grain structure of the parts belonging to both designs were examined. As a result of the examination, it was determined that the grain structures were similar.

In the hardness screening test, measurements were made on the same points of the same operation step. As shown in Table 3, the elimination of the head preparation operation was evaluated to be the difference less than 10% in the hardness of the piece.

Acknowledgement

Authors would like to thank the researcher Enes Karakaya and Nihan Aktokluk who contributed to the preparation of this publication.

Author Contributions

Alper Baygut: Drafted and wrote the manuscript, performed the experiment and result analysis.

Osman Çulha: Drafted and wrote the manuscript.

Ethics

There are no ethical issues after the publication of this manuscript.

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