Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 12 NO: 4 PAGE: 959-968 YEAR: 2023
DOI:10.17798/bitlisfen.1295905

Design, Finite Element Analysis and Optimization of Helical Angular Pressing (HAP) Method as a Novel SPD Technique

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Keywords: ECAP, SPD, Helical Angular Pressing (HAP), Finite Element Analysis.

Abstract
Severe Plastic Deformation (SPD) processes improve the mechanical properties of materials by obtaining Ultra Fine Grained (UFG) materials, orienting the grains and reforming the grains. Helical Angular Pressing (HAP) is a newly proposed Severe Plastic Deformation (SPD) method. In order to improve the efficiency of the HAP method, its die geometry should be optimized first. In this context, four parameters (helical diameter, helical pitch, helical height and channel radius) were determined for the die channel geometry, each with four levels according to the literature. Then, thanks to Taguchi L16 combinations, 16 Finite Element Analyses (FEA) were carried out using Deform 3D software instead of 256 simulations, and effective strain values and maximum pressing load values were obtained. Later on, using the SPSS 16 software, Taguchi optimization was carried out to obtain the optimum HAP die channel geometries by minimizing the press load and maximizing the effective strain values. Next, the Finite Element Analysis (FEA) was repeated with these determined optimum die channel parameters. Finally, the efficiency of this novel HAP method was compared with conventional Equal Channel Angular Pressing (ECAP) and Twist Extrusion (TE) methods. As a result, HAP method provides effective strain values equivalent to 10 number of passes after processing with ECAP. And it is approximately 4 times higher than that achieved by TE processing. As a result of the Taguchi optimization, it is concluded that the values in the combination of diameter (d)=60 mm, height (h)=50 mm, radius (r)=4 and pitch (p)=1.25 are the optimum die geometry. In conclusion, these results indicate that the proposed novel HAP method is an efficient and applicable SPD technique.

1. Introduction

In the field of materials science, the development of novel processing techniques to customize the microstructure and properties of metals and alloys is a major area of research. Among these techniques, Severe Plastic Deformation (SPD) have emerged as promising methods to produce ultra fine grained (UFG) materials with exceptional mechanical properties [1]–[5]. UFG materials produced by ECAP and SPD have shown excellent mechanical properties, such as high strength, ductility, and fatigue resistance, making them promising candidates for structural and load-bearing components. Additionally, SPD-processed materials have shown improved wear resistance and corrosion resistance, making them suitable for various tribological and corrosion-resistant applications [2], [6]–[10]. Thanks to these enhancements, SPD has been extensively investigated for their potential applications in various industries, including aerospace, automotive, biomedical, and energy.

SPD techniques involve subjecting a material to high pressure and shear forces, leading to severe plastic deformation. SPD can produce materials with ultrafine grains and a high density of defects, such as

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Received: 11.05.2023, Accepted: 15.12.2023

dislocations, stacking faults, and twins. The mechanical properties of SPD-processed materials are generally superior to those of conventionally processed materials due to the refinement of the microstructure and the high density of defects [11]–[13]. Some of the frequently preferred SPD techniques are Equal Channel Angular Pressing (ECAP), High-Pressure Torsion (HPT), Accumulative Roll Bonding (ARB), Cyclic Extrusion Compression (CEC), Multi-Directional Forging (MDF), Vortex Extrusion (VE) and Twist Extrusion (TE) [14]–[21]. In order to improve the efficiency of the SPD techniques some modifications also applied. Some of the well-known of these modifications are Expansion Equal-Channel Angular Pressing (Exp.-ECAP) and Hybrid Equal-Channel Angular Pressing (Hybrid-ECAP), Twist Channel Angular Pressing (TCAP), Twisted Variable Channel Angular Pressing (TV-CAP) [22]–[25]. Moreover, all these techniques are generally applied to billets or cylindrical shaped geometries. For tubular workpieces, Thin-Walled Open Channel Angular Pressing (TWO-CAP) and Parallel Tubular Channel Angular Pressing (PTCAP) methods have been developed as modified SPD technique [26], [27]. Besides, for sheet materials Repetitive Corrugation and Straightening (RCS) method is another developed as modified SPD technique [28]. Equal Channel Angular Pressing (ECAP) involves pressing a metal or alloy through a channel with two intersecting channels, where the material undergoes intense plastic deformation. The process results in a significant reduction in the grain size of the material and the formation of a homogeneous microstructure with a high density of dislocations. The grain size reduction is a result of the repetitive shearing and bending of the material as it passes through the channel, leading to an increase in the number of grain boundaries and a decrease in the average grain size. ECAP has been shown to be effective in refining the microstructure of a wide range of materials, including aluminium, copper, magnesium, titanium, and their alloys [24], [29]–[31].

The main objective of this study is to propose a new SPD technique that can be an alternative to conventional SPD methods and to examine the efficiency, applicability and processability of this proposed technique. In this context, the effective strain parameter results were obtained with Deform 3D software for efficiency analysis and compared with conventional SPD methods. In addition, to verify the applicability and processability of this novel method, maximum press load values were obtained using Deform 3D software and compared with literature results. Furthermore, apart from the improvement of the novel die geometry, it is aimed to optimize the die channel geometry of the HAP method using the Taguchi optimization method in order to further increase the efficiency and improve the applicability and processability of the method. Finally, it is aimed to obtain effective strain and maximum press load values by FEA using the obtained optimum die channel geometry.

2. Material and Method

2.1. Material

In this paper, AA5083 aluminium alloy was studied for a novel SPD technique. In this technique, both angular and helical channels are used together. Thus, a novel method that improves the efficiency of ECAP and TE methods is proposed. This new method is called Helical Angular Pressing (HAP). For this method, 4 different design parameters are considered. For each of these parameters, 4 different values were determined. Taguchi method was used for the determined parameters. SolidWorks software was used for the design with the 16 determined parameter combinations. For 16 different cases, finite element analyses were performed with Deform 3D software for AA5083 aluminium alloy material and optimum parameters were determined. The chemical composition of AA5083 alloy is given in Table 1. Finally, the best parameters were decided according to the results of the finite element analysis.

Table 1. Chemical Composition of AA5083 Alloy.

Alloy	Element (mass%)						
	Al	**Mg**	**Mn**	**Fe**	**Cr**	**Si**	**Cu**
AA5083	Bal.	4.73	0.71	0.26	0.17	0.14	0.03

AA5083 is generally used for all kinds of welded joints, tanks, and marine components where max. joint strength and high weld efficiency are required. This material finds application in various industries, such as in pressure vessels operating up to 65°C (150°F) and in a wide array of cryogenic uses. Additionally, it is utilized in constructing bridges, drilling rigs, marine components, freight cars, transportation equipment, TV towers, dump truck bodies, and missile components, showcasing its versatility. Moreover, it exhibits commendable resistance against corrosion [32].

2.2. Die Design and Dimensional Parameters

The new designed die has both angular and helical channel for SPD process. The channel diameter was specified as 10 mm. The variables in die design are helical diameter (d), helical height (h), helical pitch

(p) and die channel radius (r). Table 2 shows these four levels with their four factors for the HAP die channel.

Table 2. Design parameters for the HAP die channel.

d (mm)	h (mm)	r (mm)	p
40	40	0	0.5
60	50	1	0.75
80	60	2	1
100	70	4	1.25

CAD models of these 16 different cases, punch and workpiece were created with SolidWorks software. Figure 1 shows the 3D model and dimensional details of the die channel. For the analyses to be performed, the workpiece was designed with a diameter of 10 mm and a length of 470 mm. These values have been determined through the analysis of detailed studies in the literature.

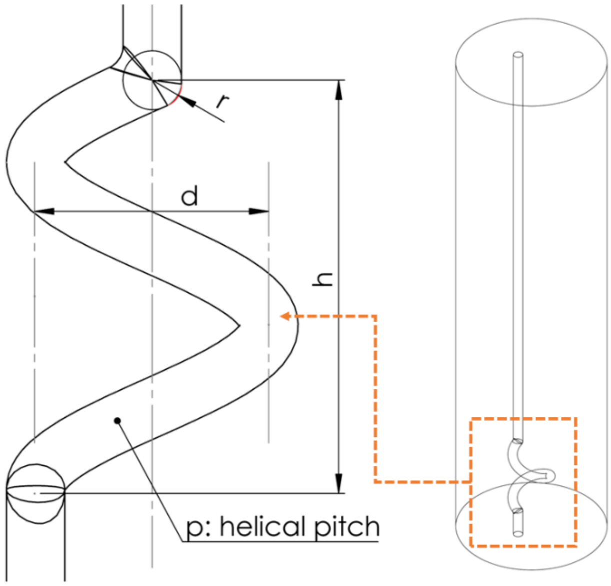


Figure 1. 3D model and dimensional details of the die.

2.3. Finite Element Analysis (FEA)

In this study, the finite element analysis method Deform 3D software was used for the simulation of the HAP method. This software is frequently preferred in SPD studies. The CAD modelling of die, workpiece and punch were designed and, were imported into the Deform 3D software. In the analysis, the die and punch are modelled as rigid and the workpiece is modelled as a plastic material. The parameters used for all analyses are listed in Table 3 in details.

In order to verify the FEA, a hexa-ECAP die model was used and analysed by Deform 3D software. The obtained effective strain value is first compared with analytically calculated value found by Iwashi and given in Equation 1 [36]. In addition, the effective strain and maximum press load values obtained are compared with literature results using the same parameters. Finally, a comparison will be made between the sample output images as a result of the FEA in this study and the reference study.

Studies have demonstrated a relationship between alterations in the mechanical characteristics of a specimen in severe plastic deformation methods and the effective plastic strain experienced by the sample during the process. The variation of the effective strain values obtained as a result of the studies in the transverse plane of the sample is also important. This is called strain homogeneity. In order to evaluate the homogeneity, effective strain values were obtained from 56 different points in the transverse plane as shown in Figure 2.

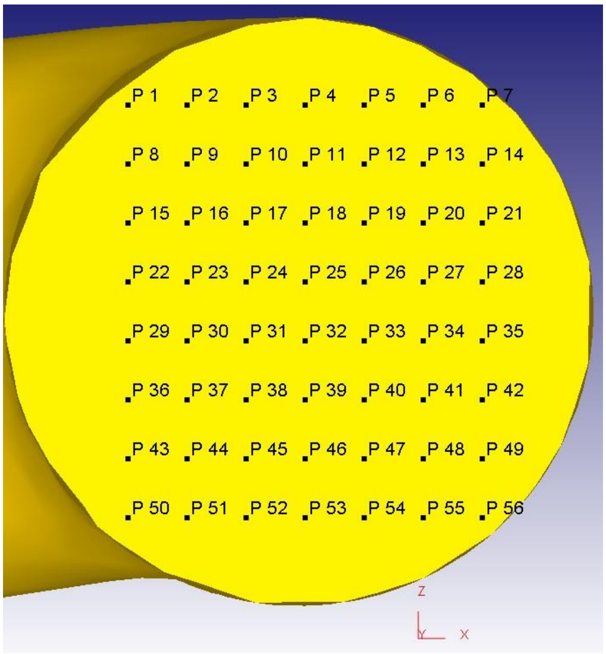


Figure 2. Pattern of points used to determine the effective strain values.

Table 3. Parameters for Deform 3D software.

Process Type	Warm forming
Temperature Calculation	Constant temperature (Isothermal)
Shape Complexity/Accuracy	Moderate/Moderate
Workpiece Shape	Whole part
Workpiece Geometry	Plastic
Top and Bottom Die Geometry	Rigid
Number of Objects	1 workpiece + 2 dies
Material	Aluminium -5083 [70-900F(40-480C)]
Temperature	200 °C
Number of Mesh	55000
Mesh type	Tetrahedron
Pressed (Movement) Speed:	1.5 mm/s
Shear Friction Coefficient	0.12

2.4. Taguchi Optimization

Traditional experimental designs are difficult to use especially when dealing with a large number of experiments and when the number of process parameters is increased. Therefore, the Taguchi method allows multiple factors to be taken into account at the same time, and it also allows the optimum result to be obtained with fewer experiments. Taguchi experimental design method is to analyses the relationship between specified parameters and output responses. With this analysis, it offers the best parameter combination according to the desired output. Thus, the number of experiments to be performed is considerably reduced and profits are made. Taguchi utilizes Orthogonal Arrays (OA) to perform multivariate experiments with a few numbers of tests. The use of OA significantly reduces the number of experiments to be performed [33]–[35].

In this study, the input processing parameters included the four-level helical diameter (d), helical height (h), helical pitch (p) and die channel radius (r). Also output responses are effective strain (ES) and maximum pressing load (ML). The ultimate goal with this method is the high ES value and low ML value of the specimen. For each input processing parameter, 4 different values were specified. Thus, using the Taguchi method with the L16 orthogonal array, the optimum processing parameters were determined with the SPSS 16 statistical software. The parameter combinations obtained by Taguchi method are given in Table 4.

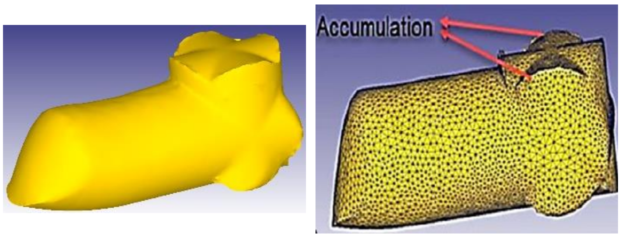
Table 4. Parameter combinations determined from Taguchi.

Cases	d (mm)	h (mm)	r (mm)	p
Case 1	40	40	0	0.5
Case 2	40	50	1	0.75
Case 3	40	60	2	1
Case 4	40	70	4	1.25
Case 5	60	40	1	1
Case 6	60	50	0	1.25
Case 7	60	60	4	0.5
Case 8	60	70	2	0.75
Case 9	80	40	2	1.25
Case 10	80	50	4	1
Case 11	80	60	0	0.75
Case 12	80	70	1	0.5
Case 13	100	40	4	0.75
Case 14	100	50	2	0.5
Case 15	100	60	1	1.25
Case 16	100	70	0	1

3. Results and Discussion

3.1. Finite Element Analyses (FEA) Results

The verification of FEA were firstly carried out by comparing effective strain results with analytical calculation. For one number of pass after ECAP process when channel angle $\Psi=90°$ and corner angle $\Phi=0°$ the effective strain value was calculated as 1.15 mm/mm (Equation 1). After FEA results with hexa-ECAP die, it is acquired as 1.12 mm/mm. So, the relative error is calculated as 2% which is acceptable for verifications. In addition, same effective strain value is obtained when comparing with the reference study. Finally, the verification is done by comparing the final shape of the workpieces after FEA results [10]. The Figure 3 illustrates the acquired workpiece geometries from carried out for this study and the reference study. When the figures are compared especially the exit shapes and accumulated areas are very similar. These similarities verify the FEA done in the scope of this study.



a) b)

Figure 3. FEA results a) caried out for this study, b) carried out by reference study [10].

The literature studies indicate that the required pressing load is maximum while the flow of the sample through the die channel is more difficult [25], [26], [30]. Therefore, it is predicted that the maximum pressing load in the HAP study will occur for the combination where the diameter (d) value is the largest, height (h) is the smallest, radius (r) is the smallest, and pitch (p) is the largest. This combination represents the most challenging flow conditions in the die channel for the HAP process. Although it is possible to predict the maximum pressing load combinations for the HAP process, predicting the effective strain value is not feasible. In general, it is thought that forcing the sample flow through the die channel leads to increased stress on the particles constituting the sample, but this forced flow does not always result in high effective strain.

L16 combinations determined by Taguchi and, FE analyses were carried out with the help of Deform 3D software and the results were analysed by acquiring the effective strain and maximum pressing load parameters. It is known that the improvement amounts of material properties as a result of SPD processes correlate with effective strain [10], [25]. The analytical calculation of effective strain for the ECAP method is given in Equation 1 [36]. Additionally, the examination of the maximum pressing load parameter shows the experimental applicability and ease of processing of the SPD process.

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)+\Psi\csc\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right] \qquad (1)$$

The obtained effective strain and maximum pressing load values are given in Table 5. When the table is analysed, it is seen that the highest effective strain value is 12 mm/mm. This value is approximately ten times higher than the analytically calculated value (1.15 mm/mm) for ECAP with one pass, obtained using Equation 1 [36]. In other words, the improvement amount obtained from a sample processed with 10 number of passes with ECAP can be achieved with a single pass with the proposed HAP method. On the other hand, the lowest effective strain value was calculated as 0.7 mm/mm. Although the proposed HAP method aimed to increase the efficiency of the traditional ECAP method, this calculated value is even worse than the traditional ECAP method. When the results obtained are compared with the Twist Extrusion (TE) method, which is another frequently studied SPD method, it is seen that the acquired effective strain value after HAP method is higher than the TE method. The study conducted by Found and colleagues suggests that for the TE method, the effective strain per pass is approximately 0.5 mm/mm when β=30°, and with their special design, a value of 3.6 mm/mm is achievable for the AA1100 material after 3 number of passes. Even this value is about one-fourth of the value obtained with the HAP process [37], [38]. Therefore, considering the material improvements, the proposed novel SPD technique has the potential to be an efficient method, but if the correct values for die geometry are not chosen, it can be less efficient than traditional methods too. In this study, this possibility led to make optimization of the die channel geometry first for the HAP method proposed.

The results given in Table 5 are compared with other methods in terms of applicability and workability with the maximum press load parameter, it is observed that it varies between 16 tons and 44.4 tons within the determined combinations. In conventional ECAP and TE methods, this value is around 6-8 tons per each pass [39], [40]. Although the pressing load values in the HAP method are about six times higher than traditional methods, this load is applied in a single pass instead of over ten passes. Therefore, while the total energy expenditure is roughly equivalent, the HAP method provides a shorter production time. As a result, it is concluded that the HAP method does not have a significant disadvantage in terms of applicability and processability compared to traditional methods and even has an advantage due to potential time savings.

In the FEA result for Case 6 parameters determined by the Taguchi combinations, it was observed that the sample could enter the first helix turn and flow was able to be achieved, but the material flow did not occur from the exit turn while continuing to compress the sample. This situation is accepted as an indication that the sample would not flow through the channel under these conditions in a real physical environment. The reason is thought to be the bending moment caused by the force applied to the sample not being in the exact center of the channel, making the flow through the die channel more difficult. Therefore, only the pitch (p) value was changed to 1.25 in the Taguchi combination, and the die drawings were redrawn then, FEA repeated as Case 6.1. But then again, a similar situation occurred in Case 6.1. Hence, the pitch (p) value had to be changed to 1 and the radius (r) value had to be changed to 2 in the Taguchi combination. These parameters were recorded as Case 6.2 and the FEA results were obtained and given in Table 5. These results were accepted as Case 6 results in Taguchi optimization.

Table 5. Finite element analyses results.

Cases	**d (mm)**	**h (mm)**	**r (mm)**	**p**	**Effective Strain (mm/mm)**	**Max. Pressing Load (ton)**
Case 1	40	40	0	0.5	12	25
Case 2	40	50	1	0.75	2.03	26.2
Case 3	40	60	2	1	2.36	31.1
Case 4	40	70	4	1.25	3.24	30.9
Case 5	60	40	1	1	5.3	32.8
Case 6	60	50	**0**	**1.25**	****	****
Case 6.1	60	50	**0**	**1**	****	****
Case 6.2	60	50	**2**	**1**	4.43	32.43
Case 7	60	60	4	0.5	2.3	33.4
Case 8	60	70	2	0.75	0.7	16.1
Case 9	80	40	2	1.25	6	31.3
Case 10	80	50	4	1	5.15	30.6
Case 11	80	60	0	0.75	11	28.5
Case 12	80	70	1	0.5	0.75	21
Case 13	100	40	4	0.75	2.7	33.3
Case 14	100	50	2	0.5	0.91	44.4
Case 15	100	60	1	1.25	7.3	34.9
Case 16	100	70	0	1	5.6	16

3.2. Taguchi Optimization Results

The signal to noise ratios values obtained as a result of Taguchi optimizations are given in Table 6. The results reveal that the most influential parameter in the optimization process is the height (h) with a delta value of 3.412, indicating its significant impact on the results. The least influential parameter is found to be the diameter (d), with a delta value of 1.448. It is concluded that the other parameters are radius and pitch parameters respectively according to the order of influence. As a result, when the priority ranking of the effective parameters is examined, it is seen that d and h values balance each other and r and p values balance each other.

Table 6. Response table for signal to noise ratios.

Level	d	h	r	p
1	5.699	5.627	4.307	6.102
2	6.879	8.076	6.201	5.209
3	5.431	6.120	6.652	5.906
4	6.476	4.664	7.326	7.268
Delta	1.448	3.412	3.019	2.059
Rank	4	1	2	3

Analysing the signal-to-noise ratio graph in Figure 4, it can be seen that the combination that gives the best result among the Taguchi L16 combinations is defined as a diameter (d) value of 60 mm, a height (h) value of 50 mm, a radius (r) value of 4 mm, and a pitch (p) value of 1.25. When calculating the optimization result, the effective strain value is a more effective output variable for decision making. Because signal-to-noise ratio was obtained at a higher level for all four parameters as illustrated in Figure 4. As the load value is related to the application, it was the second level decision maker in calculating the optimum die geometry as predicted.

When the results here are analysed in terms of HAP process, it is seen that the effective strain value is not maximum for the most difficult flow conditions. However, when the results in Table 6 are analysed, it is noted that the increase in pitch, which extends the flow path, does not necessarily lead to a significant gain in effective strain as expected, but rather increases the maximum pressing load. The actual gains in values seem to occur at the entrance and exit of the helical channel. Despite the highest pitch value being used, the radius (r) is also chosen to be the largest to facilitate flow.

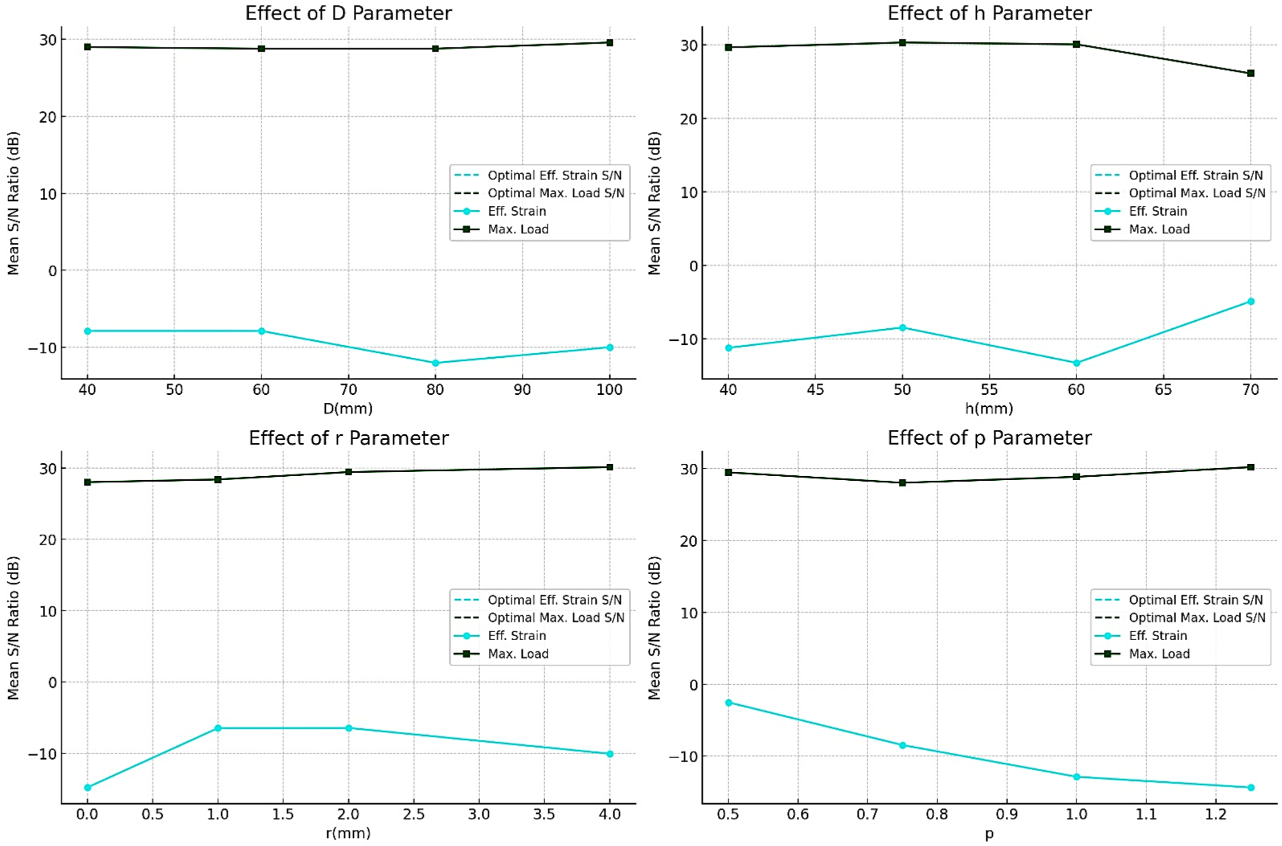


Figure 4. Signal to noise graphs after Taguchi optimization by using SPSS 16 software.

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After finding the optimum parameters through the Taguchi optimization method, the design of the HAP die was revised accordingly. Subsequently, FEA was conducted again using the Deform 3D software with the same material and parameters as shown in Figure 5. The FEA results with the optimized die geometry showed an effective strain value of 9.34 mm/mm and a maximum pressing load of 31.82 tons.

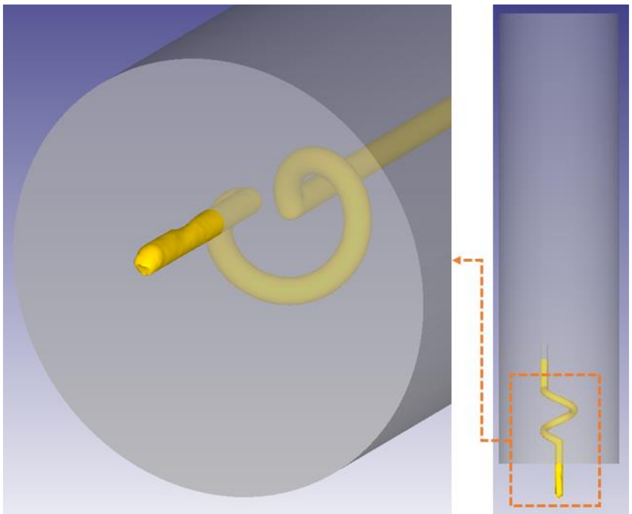

Figure 5. FEA results for optimum die channel geometry.

4. Conclusion and Suggestions

Within the scope of this study, a novel SPD method called Helical Angular Pressing (HAP) has been proposed to the literature. The efficiency, applicability, and workability of this novel method were investigated. The die channel geometries were analysed using FEA, and optimized for maximum effective strain and minimum pressing load through Taguchi optimization technique.

The obtained results can be summarized as follows:

- The maximum effective strain value was achieved as 12 mm/mm, comparable to the results of 10 passes through ECAP method. In addition, when this result is compared with TE, it is approximately 4 times higher than the value obtained as a result of TE processing.
- The minimum effective strain value was calculated as 0.7 mm/mm. This value is even worse than the conventional ECAP method. The HAP method has the potential to be more efficient than the conventional ECAP or TE methods. For this reason, it is crucial for its efficiency to optimize the geometry of the die channel firstly.
- The average pressing load obtained (around 30 tons) is approximately four times higher than ECAP and TE methods (around 8 tons), but the gains with HAP are achieved in a single pass, which potentially reduces total energy expenditure and processing time.
- As a result of the Taguchi optimization, the order of the effect of the die channel geometries on the optimization result is as h, r, p and d respectively.
- When the signal-to-noise ratios resulting from the Taguchi optimization were investigated, the combination of diameter = 60 mm, height = 50 mm, radius= 4 mm and pitch= 1.25 were found to be the optimal die channel geometry for HAP method. Repeating the FEA with these optimum values, the effective strain value was achieved as 9.34 mm/mm and the maximum press load value was acquired as 31.82 tons.

In summary, the HAP method, as a new SPD technique, is found to be more efficient, applicable, and workable compared to traditional ECAP and TE methods. It's expected to contribute significantly to future research and applications in this field.

Future Works

1. Within the scope of this study, only 16 analyses were performed for the parameters determined by Taguchi combination. Therefore, the effects of die geometries on effective strain and maximum press load were not discussed. In future studies, these effects can be investigated by performing analyses with FEA and/or experimentally with different die geometries.
2. Within the scope of this study, only FEA was performed for the HAP method proposed for the first time. It is obvious that it is very difficult to produce die channel geometry with today's technology. However, it is thought that the HAP die in question can be produced more easily, especially as a result of rapid developments in additive manufacturing methods. Therefore, experimental validation of this study's findings may be feasible in the future.

Acknowledgment

The author would like to thank Dr. Mehmet Akif YERLİKAYA for his helps during optimization process of this study.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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