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Design of Experiment (DOE) for Vibration Horns Using Modal Analysis to Improve Resonant Frequency in the Simple Shear Extrusion Process

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ABSTRACT

In most studies conducted to transmit ultrasonic vibrations to the target workpiece, vibration concentrators (horns) are employed, whose design, simulation (modal analysis), and manufacturing is critical. The use of vibration horns in the simple shear extrusion process, aimed at reducing the forming force, has been investigated both through simulation and experimentally. The effects of input parameters of the concentrators, including element type (cylindrical, conical, and exponential) and geometric dimensions, on the output parameter of resonant frequency have been examined. Design of experiments (DOE) based on the response surface methodology (RSM) and the Box-Behnken design was employed to precisely investigate and analyze the effects of each input parameter and their interactions on the resonant frequency. The design of experiments for the concentrators was conducted using Minitab software version 2019, while the process simulation was performed through modal analysis in Abaqus/Explicit software. The results indicated that to optimize the input parameters and achieve the maximum resonant frequency, the optimal element type across all three vibration zones is exponential. Furthermore, the vibration zone diameter and transducer connection zone diameter were found to have minimal impact and were eliminated. A comparison of the resonant frequency of the vibrating horn from modal analysis simulation with experimental vibration test values showed an error of less than 2%, indicating the high accuracy of the process. After obtaining the optimal horn parameters, the combined process of simple shear extrusion with the vibrating horn was simulated. Subsequently, a comparison and validation of the finite element simulation results for the forming force with the experimental values were carried out. The results from the experimental tests and the simulation of the combined simple shear extrusion process with the vibrating horn showed an error margin of 9%, confirming the efficacy of the new process.

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1. Introduction

Severe plastic deformation (SPD) methods are used to improve the microstructural properties of materials down to the nanoscale without causing any significant change in the overall dimensions of the sample, and they are also gaining popularity among researchers [1]. The change in grain size is accompanied by the formation of various lattice defects and specific microstructural

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features, which lead to the enhancement of the material's mechanical properties [2]. The simple shear extrusion (SSE) process is one of the plastic deformation methods first proposed by Pardis and Ebrahimi [3]. In this method, the material is extruded through a plastic deformation zone with a specific profile and exits from the end of the die channel. Ebrahimi et al. [4], in a study, utilized cylindrical channels instead of square channels in the shear extrusion method and reported results that included reduced friction force, increased die life, and decreased production cost. Bagherpour et al. [5] investigated the effect of the number of extrusion passes on microstructural improvement. They demonstrated that, in addition to grain refinement, the material's hardness was also significantly increased. Bayat Tork et al. [6] conducted their studies on the extrusion of a magnesium alloy using the simple shear extrusion method and reported the results as microstructural improvement and preservation of the sample's geometric dimensions (without destruction). The use of ultrasonic vibrations with different oscillation amplitudes has extensive applications across various industries, such that it can also be utilized to increase production efficiency. The transmission and propagation of ultrasonic vibrations are classified into four types: longitudinal, transverse, surface, and Lamb waves [7]. In longitudinal vibrations, the direction of particle oscillation is parallel to the direction of wave propagation, a common example of which is sound waves. In transverse vibrations, however, the oscillation direction is perpendicular, an example being light waves [8, 9]. A concentrator (horn) is an amplifier and transmitter of ultrasonic vibrations, the design and manufacture of which is based on precise acoustic and mechanical principles. For manufacturing a horn, four factors are of particular importance: selecting the type of element, choosing the desired material, determining the sample dimensions, and selecting the horn design method [10]. In most horn designs, the finite element method (FEM) simulation (modal analysis) is used to enhance the efficiency of vibration concentrators, and many researchers consider multi-element horns for fabrication. Lee et al. [11] presented a multi-element model for the motion of a concentrator. Sherrit et al. [12] proposed a multi-element concentrator for use in confined spaces. Amini et al. [13] designed and built multi-element horns for the ultrasonically assisted turning (UAT) process. Moriwaki and Shamoto [14] introduced a new hybrid horn that applies elliptical vibrations to the cutting tool in turning operations. Emami et al. [15] introduced a multi-element horn with a rectangular cross-section for the grinding process. Ahmadi et al. [16] experimentally demonstrate that superimposing longitudinal ultrasonic vibrations during the ECAP of pure aluminum significantly enhances the process by improving grain refinement and microstructural homogeneity. The results confirm that higher ultrasonic amplitudes yield finer, more uniform grains and superior tensile strength compared to conventional ECAP. Djavanroodi et al. [17] successfully used a validated 3D finite element model to analyze the effect of ultrasonic vibrations on the ECAP process of pure aluminum. Their findings demonstrate that this application significantly reduces the required forming force, with a specific instance showing a 13% decrease. The study further identifies that higher vibration amplitude, frequency, friction, billet length, and die channel angle all lead to a greater force reduction. A key challenge in ECAP, as noted by Eskandarzade et al. [18], is the high forming force from friction. While ultrasonic vibration can reduce this force, its simulation with a constant ram speed is complex and costly. This study demonstrates that artificially increasing RAM speed to save time is invalid, as it misrepresents the vibration's role. The authors therefore propose a novel alternative method that accelerates the simulation by up to tenfold without compromising accuracy. Fakheri et al. [19] investigated the influence of ultrasonic assisted equal channel angular pressing (UA-ECAP) on commercial pure titanium, with a focus on its microstructure, mechanical properties, and corrosion behavior. The UA-ECAP process effectively transformed the initial microstructure into ultrafine grains, resulting in a substantial enhancement of mechanical strength and hardness. Remarkably, the processed material exhibited a corrosion rate in hydrofluoric acid (HF) solution that was approximately 50% lower. Kumar et al. [20] investigated the optimization of rotary ultrasonic drilling machining by using the response surface methodology (RSM) and developed a model with a 5% error and 95% confidence level. Moghaddas [21] employed the response surface methodology to model and optimize torque and surface roughness in ultrasonically assisted drill machining, ultimately optimizing the process for torque minimization using low spindle speed and high vibration amplitude. Balali et al. [22, 23] studied the effects of applying ultrasonic vibration in the simple shear extrusion process. Their results showed a significant reduction in forming force and an improvement in mechanical and microstructural properties when using the new ultrasonically assisted simple shear extrusion (USSE) method compared to the conventional SSE method. In another study, Balali et al. [24] investigated the optimization of effective parameters of vibrational horns (including horn type and geometric dimensions) in the simple shear extrusion method. The findings indicated that geometric dimensions and horn type have the most significant impact on the transmission efficiency and the ability to concentrate ultrasonic vibrations. This study introduces key methodological advancements beyond prior research by fundamentally shifting the optimization approach for ultrasonic horns. Unlike previous works that used fixed geometries and overlooked resonant frequency, this research establishes resonant frequency optimization as central to enhancing process efficiency. Furthermore, this research systematically investigates for the first time the influence of individual element types within the concentrator, enabling the identification of optimal element combinations. This study employs ultrasonic vibrations to improve the mechanical and microstructural outcomes of the simple shear extrusion process. The effectiveness of this new ultrasonic-assisted SSE (USSE) method hinges on the efficient transfer and concentration of vibrations onto the sample. To design an optimal horn for this purpose, a hybrid approach was adopted, combining response surface methodology with a Box-Behnken Design. This methodology was used to analyze how key geometric parameters (A-E) influence the objective of maximizing resonant frequency. Modal analysis simulations complemented the statistical design to evaluate and validate the horn's performance. Following this optimization, a physical horn was precisely machined according to the finalized dimensions and specifications, and the custom horn was then successfully integrated into the SSE die to enable experimental validation and correlation with simulation data.

2. Materials and Methods

2.1. Experimental test procedure

To utilize concentrators (horns) and transfer vibrations to the target surface, a set of equipment including a generator, a transducer, and a booster is required, as shown in Fig. 1. The experimental tests for the simple shear extrusion process were conducted using a 100-ton universal testing machine, which also features adjustable ram speed capability. The samples used in the simple shear extrusion process, along with the vibrating horns, are made of commercial pure copper. After being machined to the dimensions of the die's entry channel (14 × 14 mm with a length of 60 mm), the samples are prepared for an annealing operation. This annealing is performed at a temperature of 630 °C for a duration of two hours. The extrusion process is carried out such that the samples are pressed by the punch and, while receiving ultrasonic vibrations, pass through the plastic deformation zone of the channel, as illustrated in Fig. 2.

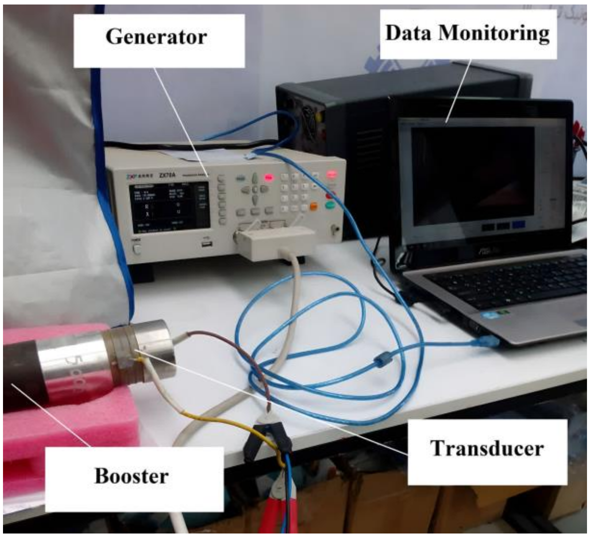

Fig. 1. Ultrasonic vibration laboratory equipment.

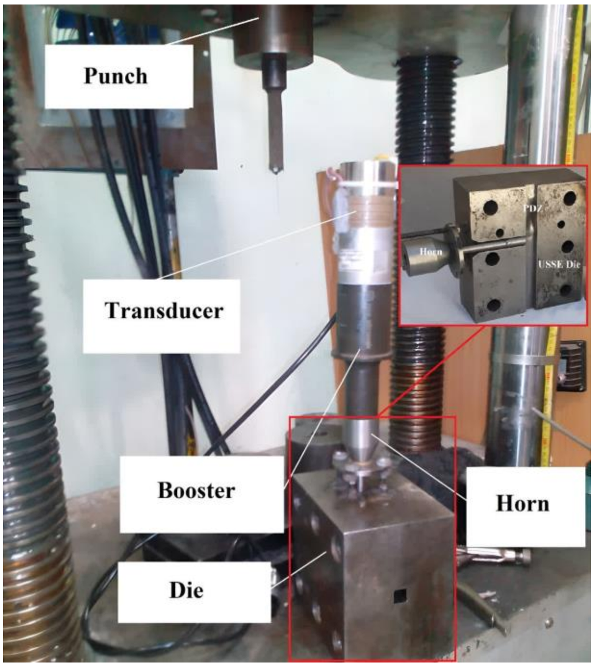

Fig. 2. The experimental setup for simple shear extrusion with ultrasonic vibrations.

The transmission and concentration of ultrasonic vibrations to the extruded samples are of particular importance in the simple shear extrusion process. To this end, response surface methodology, experimental design and modal analysis simulation are used to achieve optimal output values (i.e., maximum resonant frequency). Response surface methodology is a practical approach in the field of design of experiments (DOE) for the mathematical modeling and analysis of engineering processes [25]. In this method, a set of input parameters is varied within a specific range, and ultimately, the optimal output parameters are extracted such that the modeling error remains within an acceptable range [26, 27]. The goal of experimental design in most research is to minimize the number of computational and experimental tests, as well as to increase the efficiency of the production process. In this study, five input factors were used to achieve the maximum longitudinal mode resonant frequency in the vibration horns: the transducer connection area (A), the middle section of the horn (B), the vibration section of the horn (C), the diameter of the vibration section (D), and the diameter of the transducer connection area (E). Fig. 3. shows a schematic of the types of elements and the geometric dimensions of the horns as input factors. The response surfaces for each factor were determined based on the range of experimental tests, as shown in Table 1.

In this research, the Response Surface Methodology (RSM) and the Box-Behnken Design (BBD) were used to design the experiments. Considering five input factors, a total of 46 experimental runs were designed, as shown in Table 2. The resulting values for the resonant frequency of the ultrasonic horns were obtained based on the input parameters using the finite element analysis (FEA) software ABAQUS and its modal analysis module, which will be discussed in the following section. To achieve a 95% confidence level, only p-values less than 0.05 were considered statistically significant. The Box-Behnken Design (BBD) was selected over the Central Composite Design (CCD) due to its avoidance of undefined levels for qualitative factors, which is critical for assigning physically meaningful values in finite element software like ABAQUS. Based on the stated rationale, the Box-Behnken design was chosen as the sole methodology capable of effectively facilitating the design of experiments for the input parameters. Following the selection of this method, 46 runs were degenerated using Minitab software, incorporating five input factors (A-E). The range for each input parameter was defined according to the geometric constraints of the concentrator's placement within the USSE die. These constraints specifically limited the maximum achievable small diameter, vibration zone length, and large diameter. The defined ranges ensured the design space was both practical and physically realizable.

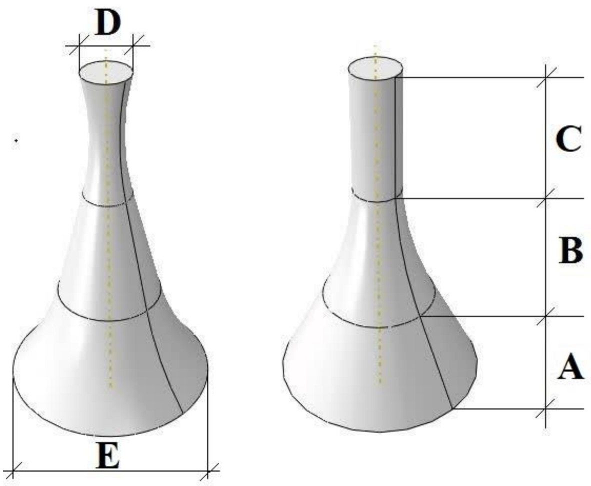

Fig. 3. Schematic of the input variables in vibrational horns.

Table 1. Design matrix of input parameters

Factors	Symbol	Unit	-1	0	1
A	Transducer connection area	-	Cylindrical element	Conical element	Exponential element
B	middle area	-	Cylindrical element	Conical element	Exponential element
C	Vibration area	-	Cylindrical element	Conical element	Exponential element
D	The diameter of the vibration area	mm	50	54	58
E	Diameter of the transducer connection area	mm	86	88	90

Table 2. Experimental design based on the Box-Behnken design

Experiment numbers	A	B	C	D (mm)	E (mm)
1	-1	0	0	58	88
2	-1	0	0	54	90
3	1	0	0	50	88
4	0	0	0	50	86
5	0	0	-1	54	86
6	0	1	0	50	88
7	0	0	0	54	88
8	0	0	0	54	88
9	0	0	0	54	88
10	0	0	0	54	88
11	0	1	0	54	90
12	1	0	0	54	90
13	0	1	-1	54	88
14	0	0	0	58	90
15	0	0	-1	50	88
16	1	0	0	54	86
17	-1	-1	0	54	88
18	0	-1	0	50	88
19	1	0	1	54	88
20	0	-1	-1	54	88
21	-1	0	-1	54	88
22	1	-1	0	54	88
23	-1	1	0	54	88
24	0	0	1	58	88
25	0	-1	1	54	88
26	-1	0	0	54	86
27	0	0	1	50	88
28	0	1	1	54	88
29	0	0	0	54	88
30	0	-1	0	54	86
31	0	0	1	54	86
32	0	0	-1	58	88
33	0	0	0	58	86
34	0	1	0	54	86
35	-1	0	0	50	88
36	1	0	0	58	88
37	0	-1	0	58	88
38	0	0	0	54	88
39	0	0	0	50	90
40	0	1	0	58	88
41	1	0	-1	54	88
42	0	-1	0	54	90
43	1	1	0	54	88
44	0	0	-1	54	90
45	0	0	1	54	90
46	-1	0	1	54	88

2.2. Modal analysis simulation of vibration concentrators (Horns)

The modal analysis simulation method was employed to circumvent experimental testing, which is not time- or cost-effective, and to avoid numerical methods that involve a high computational load. The modal analysis simulation of the horn is an essential tool for design optimization, preventing the phenomenon of destructive resonance and ensuring vibration transfer quality and product durability. The modal analysis simulation of the vibrating horns, with various element types and variable dimensions, was performed using the ABAQUS/Explicit software. In this method, the geometry and dimensions of the vibrating horn are first drawn in the Part module of ABAQUS, with the capability to alter the element type and the horn's dimensions. Subsequently, in the Property module, the values for density and elastic properties (Young's modulus and Poisson's ratio), corresponding to the horn's material, are entered; these values are presented in Table 3. The model's boundary conditions were rigorously defined to replicate the physical constraints of the component within its operational fixture. The Lanczos eigen solver was employed for its proven efficiency in extracting the first ten mode shapes from the large-scale, linear structural system. The resonant frequency in the modal analysis was determined using the 'Step' module and the 'Frequency' section. This involves defining the frequency range (i.e., the maximum and minimum resonant frequencies). For instance, the 19- 21 kHz range was selected due to the horn's support (boundary) conditions and connection to the booster. For mesh Convergence and Justification, a comprehensive mesh convergence study was conducted, resulting in a final mesh density that ensures the calculated natural frequencies for the modes of interest are independent of additional element refinement.

Finally, the results of the horn's modal analysis were obtained in the Visualization module, as illustrated in Fig. 4.

The vibration amplitude for the same comparison of the vibration horns obtained by the input parameters of the experimental design was considered to be 25 μm in all experiments. The maximum resonance frequency (the output factor) was determined from a modal analysis of the vibrating horns, which was based on the independent input factors A, B, C, D, and E. By importing the results from the modal analysis of the vibration concentrators into Minitab software, the optimal horn for use in the simple shear extrusion process and for experimental applications can be identified. After obtaining the optimal parameters for the vibrating horn, the concentrator is modeled within the simple shear extrusion process, and a finite element simulation is performed in Abaqus/Explicitto validate the results against experimental tests, as illustrated in Fig. 5.

Table 3. Mechanical properties of the vibration concentrators

Material	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
H13 Tool Steel	7850	210	0.35

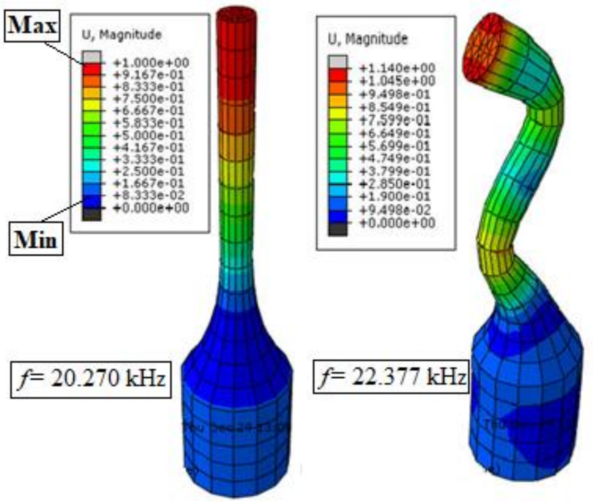

Fig. 4. Comparison of cylindrical-exponential-cylindrical horn resonance frequencies for two longitudinal and bending modes.

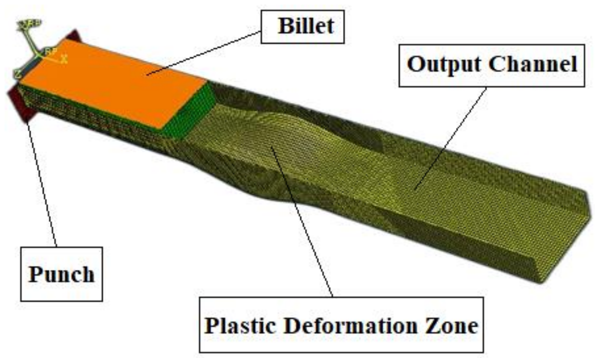

Fig. 5. Finite element model of the simple shear extrusion process.

3. Results and Discussion

3.1. The effect of input parameters on the resonant frequency

Following the analysis of the output parameters based on the input parameters, the results of the analysis of variance (ANOVA) for the resonant frequency in vibrating horns were extracted, taking into account the estimates of the linear, quadratic, and interaction effects of the variables. The ANOVA results are presented in Table 4. Furthermore, the significant factors and the percentage contribution of the input parameters to the resonant frequency were also extracted. Input parameters with a P-value of less than 0.05 and larger F-values have a greater effect on the resonant frequency; consequently, input parameters D and E were eliminated. Subsequent statistical analysis identified only linear parameters of the element types as significant influencing factors, and quadratic and interaction terms were removed, resulting in a revised model. The model's exceptional adequacy was verified through residual plots, confirming adherence to key regression assumptions. This is further substantiated by a remarkably high Adjusted R^2 of 98.78% for the resonant frequency. The strong concordance with a predicted R^2 of 97.18% underscores the model's accuracy and reliability for forecasting as shown in Table 4, the ANOVA results demonstrate that the horn's vibration section (Parameter C) and its middle section (Parameter B) are the most influential factors on the resonant frequency, with substantial contribution percentages of 48.43% and 17.14%, respectively. After identifying the significant and important factors through the ANOVA test, the coefficients for the mathematical model of the output parameter (resonant frequency) were also extracted and are expressed by Eq. (1).

$$Resonance\ Frequency\ (kHz) = 19.5442 + 0.384A + 0.715B + 0.408 \quad (1)$$

In this research, the calculated R^2 value for the resonant frequency of the vibrating horns was obtained as 98.78%, which confirms the high accuracy of the proposed model and is illustrated in Fig. 6. Fig. 7 shows the scatter plot of the main effects and the levels of the input factors on the resonant frequency of the vibrating horns. The results indicated that the input parameters D and E were not identified as significant factors and were removed due to their P-values being above 0.05. The influence of cylindrical, conical, and exponential geometries on three parameters, the transducer connection area (A), the central horn area (B), and the horn vibration area (C) was investigated. The exponential geometry demonstrated the most significant effect on increasing the resonant frequency across all three areas. In investigating the superior performance of exponential horn elements across all sections, this behavior is attributed to a more favorable stress wave propagation profile. The exponential contour facilitates a smoother impedance matching, which minimizes wave reflections and more effectively channels acoustic energy toward the output section. This results in a higher vibration amplitude and overall efficiency compared to the linear and stepped configurations.

The sensitivity of the resonant frequency to individual input parameters is non-uniform and interdependent, necessitating a systematic optimization strategy. This study employs a dedicated methodology for vibrating horn design, with the explicit objective of resonant frequency maximization. The underlying physical principle relies on the manipulation of the horn's acoustic impedance profile along its axis. By configuring the three critical geometric factors, the transducer connection area (A), the central area (B), and the vibration area (C) as concurrent exponential functions, the horn's geometry transitions smoothly. This continuous, exponential contour minimizes internal wave reflections and destructive interference, thereby efficiently channeling mechanical energy. Consequently, the system can achieve a higher natural oscillatory state, which is quantitatively observed as an increase in the resonant frequency. The graphical representation of this optimization criterion in Fig. 8 effectively captures this synergistic relationship, demonstrating that the concurrent exponential tuning of parameters A, B, and C constitutes the condition for peak resonant performance.

Table 4. The results of the analysis of variance (ANOVA) for the resonant frequency

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-value
Model	3	9.9138	70.20%	9.91385	3.30462	18.06	0.000
Linear	3	9.9138	70.20%	9.91385	3.30462	18.06	0.000
A	1	1.7718	12.55%	1.77178	1.77178	9.68	0.005
B	1	6.1404	43.48%	6.14042	6.14042	33.56	0.000
C	1	2.0017	14.17%	2.00165	2.00165	10.94	0.003
Error	23	4.2081	29.80%	4.20811	0.18296		
Lack-of-fit	21	4.2081	29.80%	4.20811	0.20039	*	*
Pure error	2	0.0000	0.00%	0.00000	0.00000		
Total	26	14.1220	100.00%				

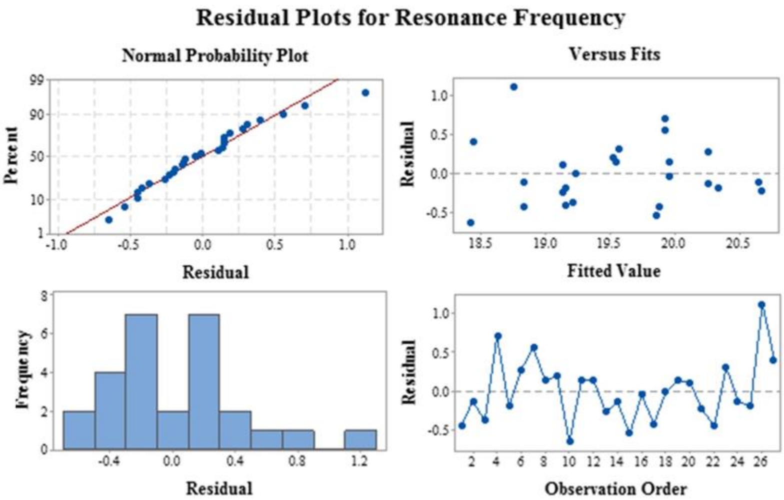

Fig. 6. Residual plots used to validate the finite element model of the vibrating horns.

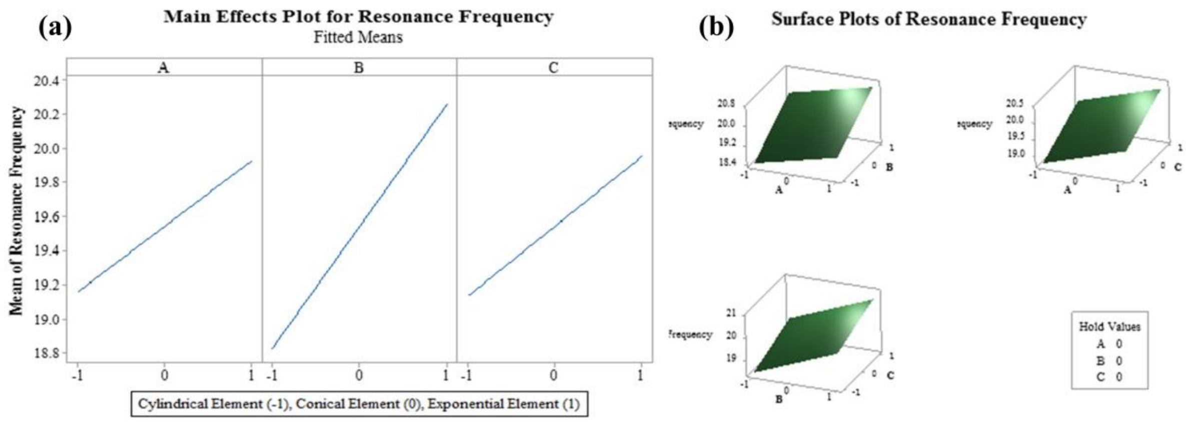

Fig. 7. Illustrates (a) the main effects plot and (b) the response surface plot for the resonant frequency.

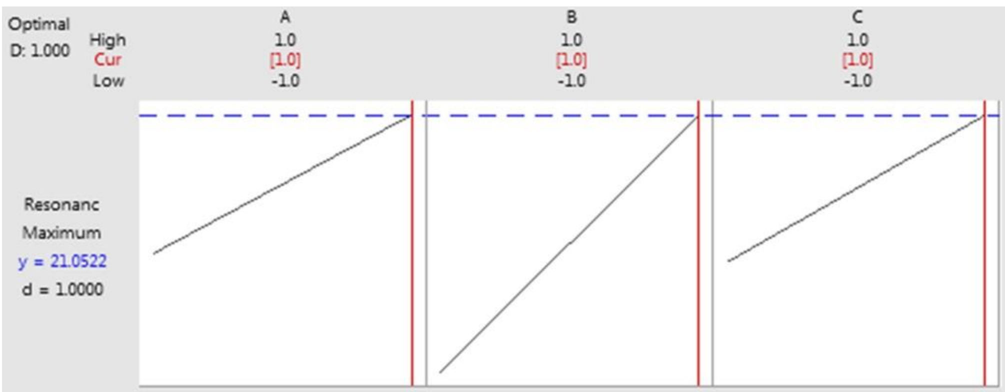

Fig. 8. Optimization results targeting the maximum resonant frequency.

A critical validation step was performed following the DOE analysis. The optimized input parameters, which predicted an optimal resonant frequency of 21.0522 kHz, were independently verified through a subsequent modal analysis in Abaqus. The result of this validation run was a frequency of 20.742 kHz, demonstrating acceptable agreement with the initial DOE prediction and confirming the robustness of the optimization process.

3.2. Validation of experimental and simulation data

Following the determination of the optimal parameters via modal analysis, the horn was manufactured using a 212-model lathe. Given the precision of this lathe, a manufacturing tolerance of ±0.01 mm was assigned. Subsequent turning operations were performed to machine the horn's major and minor diameters, and its exponential profile was shaped using a form tool. The surface finishing of the concentrator was carried out using six different grades of sandpaper. The final polishing was achieved by rotating the chuck and using P600-grit sandpaper. To report its resonant frequency, the vibrating horn underwent vibration testing. The resonant frequency of the longitudinal mode of the vibrating horn in the simulation state was 21.0522 kHz. A comparison with the experimental value of 21.319 kHz revealed an error of 1.27%. Given the small error percentage, the high efficiency of the optimized horn was confirmed. It was also determined that the finite element simulation (modal analysis) of the vibrating horn possessed high accuracy. The optimized horn was manufactured and assembled within the die. An initial frequency mismatch between experiment and simulation was observed, which was attributed to energy dissipation and damping. This mismatch consequently led to a significant error in the forming force comparison. To address this, thin discs of the horn's material were inserted between the concentrator and booster. This countermeasure successfully aligned the experimental and simulated resonant frequencies. Consequently, the discrepancy between the experimental and simulated forming forces was markedly reduced. A finite element simulation of the simple shear extrusion process, integrated with the vibrating horn, was performed to report the forming force. The extracted values were then compared with experimental values. A comparison of the forming force diagram for the simple shear extrusion process under applied ultrasonic vibrations, for both simulated and experimental states, showed an error of 9%, as indicated in Fig. 9. The article text explicitly emphasizes that the optimized exponential profile not only improves energy transfer efficiency but also directly influences key parameters of the simple shear extrusion process. This, in turn, governs the resultant resonant frequency and, ultimately, the forming force. This finding offers a practical strategy for reducing energy consumption and enhancing productivity in metal forming industries.

Simple shear extrusion process imposes immense strain to refine microstructures and enhance mechanical properties, yet it requires prohibitively high forming forces. The simultaneous application of ultrasonic vibrations (>20 kHz) has emerged as an innovative solution to mitigate these forces through the "acoustic softening" effects. This force reduction stems from two primary mechanisms: the "friction effect," where vibrations convert static to kinetic friction at tool-workpiece interfaces, and the "volume effect," where vibrational energy facilitates dislocation motion, lowers flow stress, and promotes dynamic recovery. Additionally, in certain materials, vibrations can induce superplasticity through accelerated diffusion and grain boundary sliding [28]. Practical applications demonstrate significant force reduction in SSE processing and improved efficiency. Consequently, ultrasonic assistance not only reduces energy consumption and tool wear but also enables greater plastic strain, thus achieving superior microstructural refinement.

Furthermore, the new hybrid USSE (Ultrasonic-assisted simple shear extrusion) method demonstrates that by transmitting ultrasonic vibrations to the samples being extruded, the friction between the sample and the die channel (the plastic deformation zone) is reduced, and consequently, the forming force is also decreased.

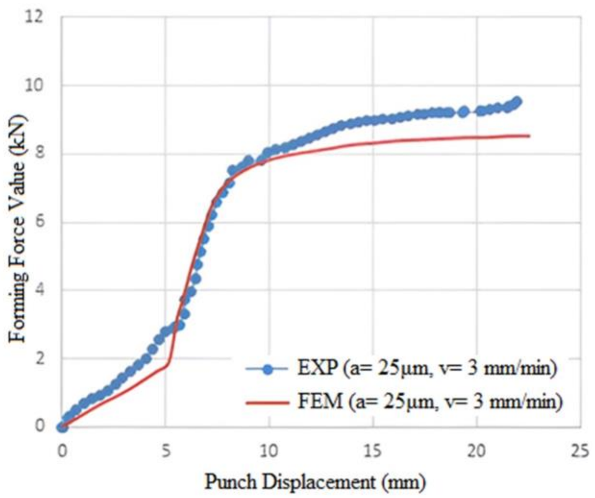

Fig. 9. Comparison of simulated and experimental forming forces in the USSE process.

4. Conclusion

In this research, the optimization of the element type and geometric dimensions of ultrasonic horns was evaluated to enhance the efficiency of ultrasonic vibrations under maximum resonant frequency. This research presents an optimization method that is broadly applicable, extending beyond the tested material to others like aluminum and superalloys. It can also be adapted to different forming processes, such as vibrational forging. The core principle involves customizing the acoustic impedance for each new application. Although this study used a specific material and geometry, it establishes a critical foundation. Future work must now validate these designs under realistic industrial conditions, and a key next step is testing their long-term durability under high-amplitude, production-level loads. The primary objective was to fabricate a high-precision and high-efficiency vibrating horn for use in the simple shear extrusion process. To this end, an experimental design of the independent input parameters (diameter of the transducer connection area A, length of the lower horn section B, length of the middle horn section C, length of the upper horn section D, diameter of the horn's vibrating section E) was conducted using Minitab and Abaqus Explicit software to achieve the maximum resonant frequency. Finally, the horn with optimal parameters, extracted from the modal analysis data, was compared with an experimental horn. The manufactured horn was then applied in the simple shear extrusion process, yielding the following key results:

- The results from the response surface methodology indicated that to achieve the highest resonant frequency, the element type in all three sections (diameter of the transducer connection area A, length of the lower horn section B, length of the middle horn section C) must be exponential.
- The input parameters (length of the upper horn section D, diameter of the horn's vibrating section E) did not significantly affect the resonant frequency of the vibrating horn.
- The coefficient of determination (R^2) for the resonant frequency prediction model was calculated as 98.78%, indicating that this model can accurately predict the results obtained from the modal analysis.
- The results of the optimal input parameters for the vibrating horn were subjected to modal analysis and experimental fabrication. A comparison of the resonant frequency from the simulation and experimental states showed an error of less than 2%, demonstrating the acceptability of the optimized parameters.
- A comparison of the forming force graphs for the simple shear extrusion process with applied ultrasonic vibrations, from both simulation and experiment, showed a 9% error, indicating acceptable accuracy of the process.
- The results demonstrated that by transmitting ultrasonic vibrations to the samples being extruded, the friction between the sample and the die channel (the plastic deformation zone) is reduced, consequently reducing the required forming force.

Conflict of interest

The author declares that there is no conflict of interest relevant to this article.

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