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INVESTIGATION OF THE IMPACT OF PRODUCT THICKNESS AND STRAIN ON COLD FORGING PROCESSES

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Abstract. This study investigates the impact of sheet metal thickness and strain generated on a cold forging process. A cold forging die was manufactured based on a numerically modelled product design that considered stress concentration die profiles. Experiments involved cold forging various sheet metals (lead, brass, aluminium, and steel) with thicknesses ranging from 2 mm to 6 mm to assess their influence on the thickness and strain. An assumption was formulated using Solidworks to determine the appropriate sheet metal thickness based on the material type. This assumption, based on volume considerations, showed practical applicability for selecting sheet metals with thicknesses close to those designed in the numerical modelling. The results revealed that softer materials, such as lead and aluminium, closely approximated the design thickness, particularly in the central region of the die profile, with error deviations of 1.14 % and 4.36 %, respectively. In contrast, harder materials demonstrated larger deviations from the design, with minimum errors of 4.94 % for brass and 5.73 % for steel. All sheet metals underwent compressive strain in the central region of the die profile due to the stamping operation. This work demonstrates a practical approach for selecting sheet metals based on material and thickness considerations, providing insights into the behaviour of different materials during the cold forging process.

Keywords: Cold forging die, sheet materials, product thickness, strain analysis.

1. Introduction

Forging, an ancient metalworking technique with origins dating back to at least 4 000 BC, was initially used for crafting jewellery, coins, and various implements through the process of hammering metal tools made out of stone [1]. Predominantly characterised as a hot working method, forging takes place at temperatures of up to 2 300 °F, however, a variant called cold forging has emerged in the form of impression die forging [2]. Cold forging encompasses a wide array of processes, including bending, cold drawing, cold heading, coining, extrusions, just to name a few, yielding a diverse range of part shapes [3]. The temperature of metals subjected to cold forging can span from room temperature to several hundred degrees. It is categorised into three primary types, namely, Cold forging, Warm forging, and Hot forging, depending on the temperature at which these processes are carried out [4].

Forging have been used since ancient times, and it was during the era of the Industrial Revolution that the demand for forged components increased significantly, prompting the development of new technologies aimed at improving production output and material quality [5]. Currently, forged parts are considered superior to their cast counterparts due to their distinctive properties, particularly grain flow [6]. Cold forging contributes to the reinforcement of metal strength by hardening it at room temperature, while hot forging results in optimal yield strength, reduced hardness, and increased ductility by hardening metal at exceedingly high temperatures [7].

Several researchers have considered sheet metal thickness and strain rate in their studies. Ahmad Baharuddin Abdullah (2007) [8] provided a summary of current developments in die design for the forging process and the associated systems, aiming to improve design processes and die efficiency. The research also addressed future challenges in the die design domain, proposing the establishment of an experimental support system to meet the consumer demands. In their study, Shrikant Jain and R. K. Ranjan (2017) [9] investigated the deformation characteristics of an aluminium-copper composite under varying strain rates, influenced by ram velocity, within the context of cold forging. The study involved forging samples at different ram velocities, namely, 1.5, 50, 100, and 150 mm min^{-1}, and assessed the forgeability by crack initiation at a corresponding percentage reduction in height. The researchers developed a mathematical model for an "upper bound" analysis of the average forging pressure on the platen during cold forging at different ram velocities, graphically depicting the relative variation in average forging pressure with the percentage reduction in height of these composite samples.

The experimental results pertaining to forgeability, at different ram velocities, considering percentage reduction in height, forging stress, compressive strength, percentage increase in bulge diameter, and linear hoop strain displayed a strong correlation with the theoretical results. Masakazu Kobayashi et al. (2018) [10] conducted measurements of 3D inhomogeneous plastic strain in cold-rolled aluminium-magnesium alloys containing small lead particles, a local strain measurement technique, with a specific focus on the impact of magnesium content on local strain and microstructure development. Synchrotron radiation microtomography was employed to obtain these measurements, with the observed local deformation significantly influencing the mechanical properties of metallic materials, including strength and formability. It was noted that microstructural development varied with the magnesium content in the aluminuim alloy, although no difference in shear strain development was observed. The strain distributions were compared to an investigated texture development conducted via SEM/EBSD. Additionally, J. Paulo Davim (2015) [11] discussed the wide range of manufacturing processes involved in material formation and machining, emphasising research and development in these areas. Gupta and Davim (2021) [12] explored advanced welding-joining and deforming techniques, covering theoretical developments and practical improvements in manufacturing processes. Dixit et al. (2011) [13] provided a comprehensive review of material behaviour modelling in metal forming and machining processes, highlighting its influence on process design and product outcomes. Petkar et al. (2023) [14] investigated the applications of natural computing algorithms in optimising cold forging backward extrusion processes, aiming to enhance punch service life and mechanical strength of forged components, particularly in automotive production. Praveenkumar M. Petkar et al. (2020) [15] employed a multi-layered feed-forward artificial neural network (ANN) model to analyse the influence of various parameters, such as billet size, reduction ratio, punch angle, and land height, in the context of cold forging backward extrusion processes. They examined the effects of effective stress, strain, strain rate, and punch force for AISI 1010 steel. The ANN model analysis revealed that increasing the billet size led to an increase in effective stress and strain with the reduction ratio, while decreasing the punch angle and land height impacted material flow and resulted in decreased process parameters, namely the effective stress, strain, strain rate, and punch force, ultimately reducing punch forces and improving the punch life. The proposed ANN model, based on finite element simulation, provided insights into the forming behaviour of the cold forging process, offering valuable guidance for process design and streamlining efforts in the cold forging industry in terms of cost and time. Felix Kolpak et al. (2021) [16] delved into the effects of anisotropic work-hardening on the cold forging process, with a particular focus on material behaviour following strain path reversals. Three steel work-hardening behaviours were characterised for large monotonic strains (up to 1.7) and subsequent strain path reversals (up to 2.5). Tensile and compressive tests conducted on the extruded material revealed a non-monotonic work-hardening behaviour. The study analysed anisotropic work-hardening phenomena, including the Bauschinger effect, work-hardening stagnation, and permanent softening across all investigations, with these phenomena intensifying with pre-strain. The experimental work assessed the influence of strain path changes, investigating cross-hardening effects. The study achieved good agreement between the experimental and numerical data by using a modified Yoshida-Uemori model capable of capturing all observed anisotropic work-hardening phenomena. Numerical constitutive models were integrated into simulations for single and multi-stage cold forming processes, revealing the impact of anisotropic hardening on projected component properties and process forces.

While previous studies have explored various aspects of cold forging, such as die design, deformation characteristics of specific materials, and the effects of anisotropic work-hardening, the unique contribution of this study lies in its exploration of the interplay between sheet metal thickness and strain induced in cold forging procedures. Delving into the nuances of cold forging die geometry and the selection of materials, it seeks to shed light on the intricate dynamics governing preproduction forging processes. This indicates a focus on understanding the early stages of forging, including the planning and design phases, which may differ from the emphasis of previous studies that primarily focus on the manufacturing aspects of forging.

2. Materials and Methods

The methodology chapter details the selection of product design with diverse geometrical profiles and the subsequent elaboration of the cold forging die design, including various components. The manufacturing of die components involved medium carbon steel, with material properties verified through testing. The cold forging process utilised multiple sheet metals, including lead, brass, and aluminium, with Solidworks software aiding in the die setup simulation and thickness assessment. Comparison of calculated and selected thicknesses validated the efficacy of the chosen thicknesses for different metals, reinforcing the cold forging design assumption. Further elaboration on these aspects is provided in the subsequent sections.

2.1. Product design

In this work, the product design under study features various geometric profiles, including grooves, sharp edge, dome, and fillets. The detailed design of the product sample, along with dimensional drawings and isometric views, is presented in Figure 1.

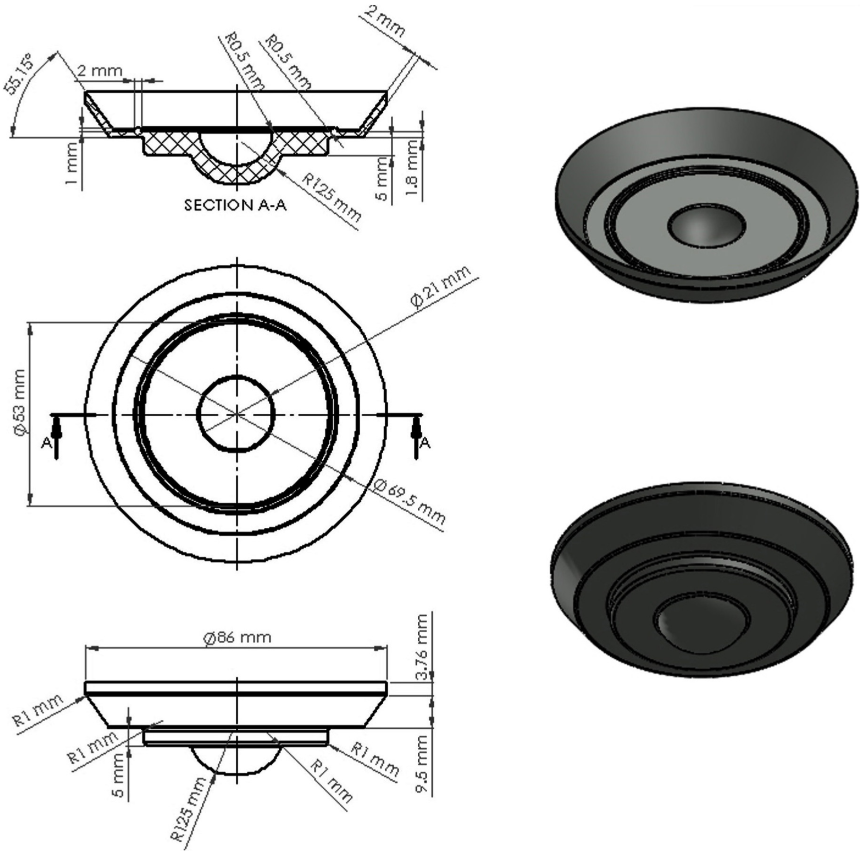


Figure 1. The details of the product design.

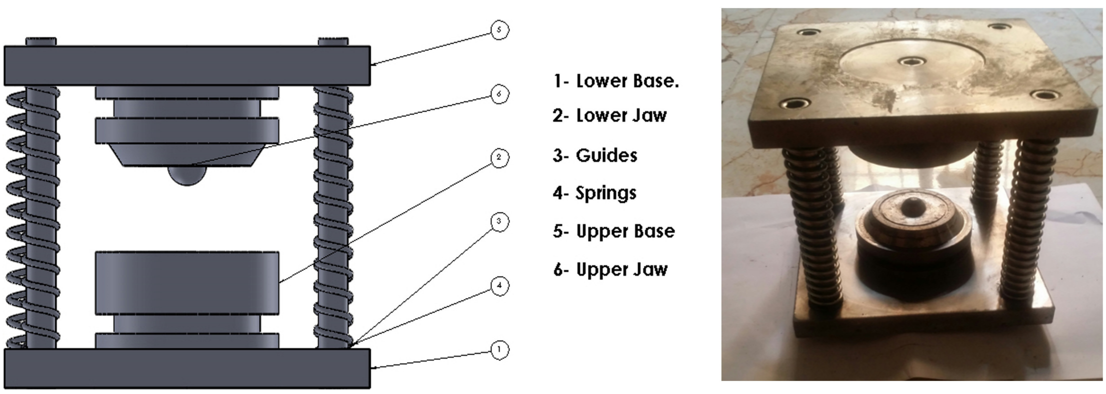


Figure 2. The design and manufacture of the cold forging die.

2.2. Design of cold forging die

Although forging commonly entails shaping metal by compressing it between dies, it is crucial to understand that forging techniques can be used for different types of metal, such as bars and sheet metal. This study specifically focused on the cold forging process applied to sheet metal forming. The term "forging die" in the current research refers to the tool used in the sheet metal forming process that applies localised compressive loads to shape the sheet metal into the desired form. In the experimental setup, the die design comprises several components, each serving a specific function, as listed below. The design and manufacture of the assembly, including the main die parts, is illustrated in Figures 2 and 3:

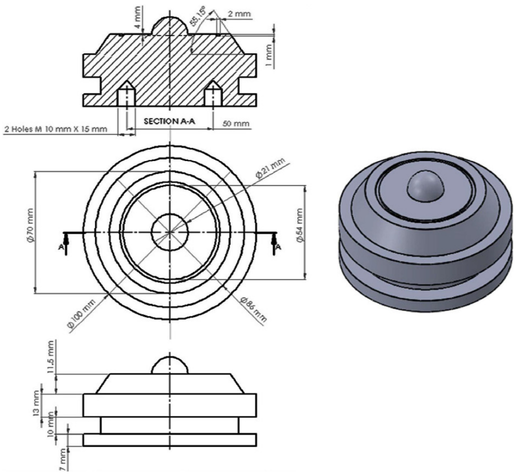
(1.) Upper and lower jaws: These components are responsible for shaping or approximating the shape of the manufactured workpiece during the forging process.

(2.) Upper and lower die bases: These parts provide support and fixation to the die jaws.

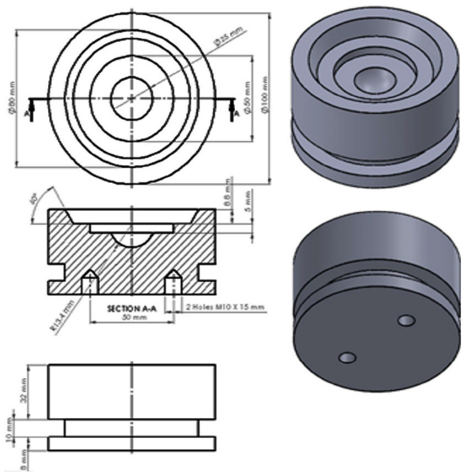
(3.) Guide pillars: These elements ensure a smooth direction and alignment of the upper and lower jaw.

(4.) Spring: This component is used to lift the upper jaw away from the manufactured workpiece after the forging process is complete.

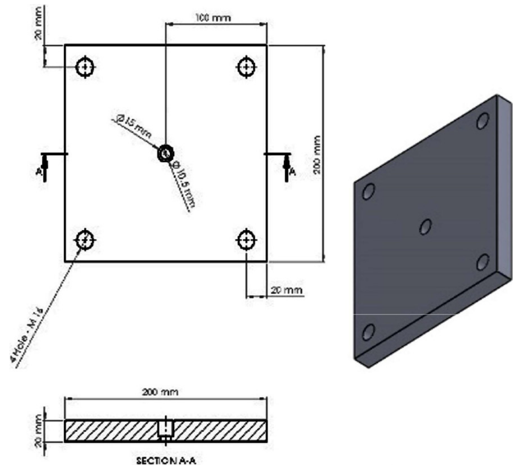
(5.) Bolts and nuts: These fasteners are used to secure the die parts together.



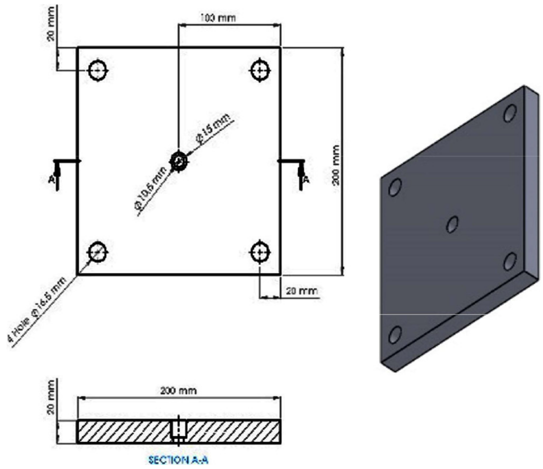
(a). Upper jaw.



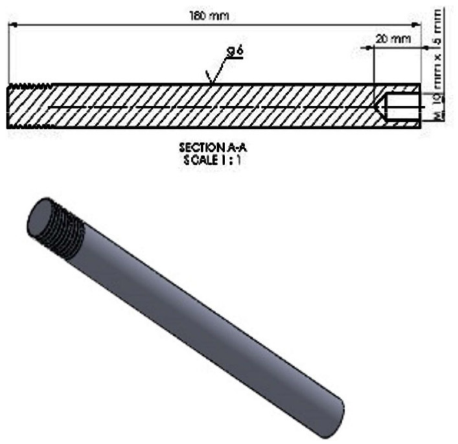
(b). Lower jaw.



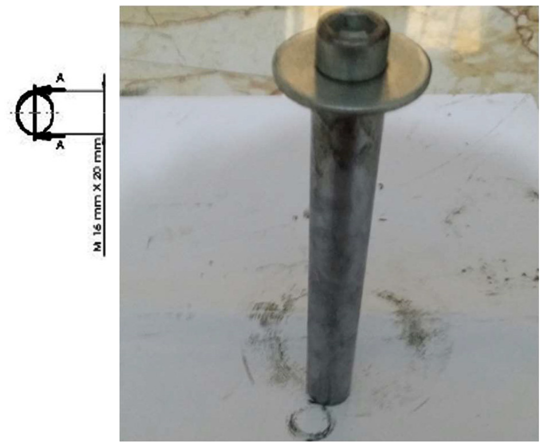
(c). Lower base.



(d). Upper base.



(e). Guide.



(f). Physical appearance of the guide.

Figure 3. The detailed design and manufacturing of the upper jaw, lower jaw, lower base, upper base, guide and physical appearance of the guide.

2.3. Manufacturing of the die

The cold forging die components are manufactured using medium carbon steel (CK45) in accordance with German standards (DIN) as is it readily available on the market. To ensure the desired material properties, test samples were analysed for chemical composition to determine the exact material type and mechanical properties required for the forging process. These testing specimens were obtained by cutting steel sheet with dimensions based on ASTM-68 standard for the tensile testing. The chemical composition and mechanical properties of the die material were provided by the General Company for Engineering Examination and Qualification, as shown in Tables 1 and 2.

Wt. %	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Al %	Cu %	Fe %
Standard [17]	0.42–0.5	0.17–0.37	0.5–0.8	≤0.035	≤0.035	≤0.25					
Tested	0.469	0.197	0.586	0.0159	0.0698	0.028	0.0045	0.0377	0.0011	0.0527	Bal

Table 1. The standard and tested chemical composition of the material.

Sample No.	Yield stress [MPa]	Ultimate stress [MPa]	Elongation [%]	Hardness [VC]
Standard [17]	355	610	20	
1	362	615	24	275
2	378	625	26	275
3	375	615	26	315
Average	371	618.33	25.33	

Table 2. The standard and tested mechanical properties of the material.

Metal alloy	Calculated thickness [mm]	Sheet thickness chosen [mm]	Thickness assessment
Lead	4.18	3	Failed
		4	Failed
		6	Succeed
Brass	4.88	2	Failed
		5	Failed
		6	Succeed
Aluminum	4.59	2	Failed
		3	Failed
		6	Succeed
Steel	3.69	2	Failed
		3	Succeed

Table 3. Thickness assessment of sheet metals for cold forging process.

2.4. Cold forging process

Several sheet metals are used for manufacturing the product to analyse the influence of the product thickness and strain obtained during the forging process, which depends on the type of the sheet metal and the shape design of the die jaws. Different types of sheet metal with varying thicknesses have been used in the cold forging processes. The metals used in forging production include lead, brass, aluminium, and steel with a thickness range of 2–6 mm. Solidworks is a comprehensive design software widely used for modelling parts and assemblies, including die structures. In this study, Solidworks was used with an assumption to determine the clearance between the jaws of the die, which is crucial for understanding the range of thicknesses achievable for various materials. By simulating the die setup in Solidworks, the available thicknesses of each material were accurately assessed. The assumption, based on the idea that the volume of the selected sheet metal type, represented as a circular plate, is equal to the designed product volume obtained from the Solidworks product model plus the volumetric extension, as represented by the equation:

$$V_{\text{selected sheet}} = (1 + \text{El}\,\%) \cdot V_{\text{design product}}. \quad (1)$$

The calculated sheet thickness for different types of metal is then determined by the equation:

$$\text{th} = \frac{4(1 + \text{El}\,\%) \cdot V_{\text{design product}}}{\pi \cdot d^2}, \quad (2)$$

where

$V_{\text{selected sheet}} = \frac{\pi \cdot d^2}{4}$,

$V_{\text{design product}} = 25\,250.13\,\text{mm}^3$,

El % the percentage elongation of the product metal as shown in Table 3.

d the sheet metal diameter before the forging process is 100 mm.

The selected thickness of the sheet metals used before the forging process, based on the calculated thickness for each type of the sheet material, is shown in Table 3.

The definitions of success and failure for the sheet metal thicknesses in Table 3 were based on the forging process outcomes. A successful thickness resulted in the desired product shape without defects, while a failure led to issues like bending or tearing. Success or failure was determined through a visual inspection and comparison with design specifications, considering deviations from the calculated values.

Figure 4. The lead sheet metal products.

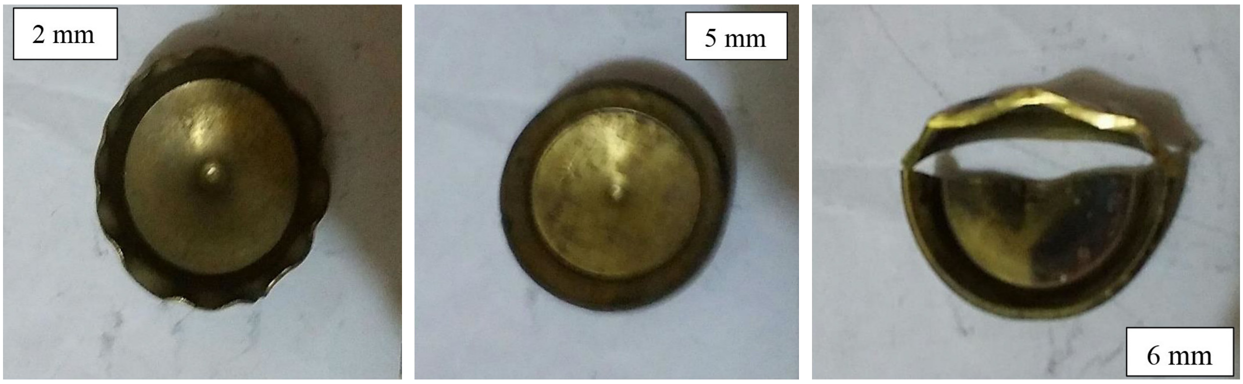


Figure 5. The brass sheet metal products.

Figure 6. The aluminium sheet metal products.

The choice of sheet thickness for all metals in Table 3 depends on the availability of metal types on the market, as detailed in the table. According to the selected thicknesses of the sheet metals, some of them, especially the softer materials like lead, brass, or aluminium, succeeded with higher thicknesses than calculated, while lower thicknesses failed. Conversely, for harder materials such as steel, the selected sheet thickness that were nearly or slightly lesser than calculated agreed with this assumption and succeeded in production, while those significantly lower failed.

Figure 4 shows the lead sheet metal products, where the thicknesses less than (3 mm) or nearly close to (4 mm) the calculated value of 4.18 mm failed due to bending inside the product, while higher thicknesses (6 mm) succeeded. Similarly, for brass sheet metal, a lower thickness (2 mm) than the calculated failed due to wrinkling, while a thickness close to the calculated one (5 mm) failed to produce the correct stamping shape, but a higher thickness (6 mm) did, as shown in Figure 5. For aluminium sheet metal, a smaller thickness (2 mm) failed due to a tearing in the middle, while a sheet with a thickness of 3 mm failed to produce the correct stamping shape; however, a higher thickness (6 mm) succeeded, as shown in Figure 6. In the case of steel sheet metal, two thicknesses were used due to its hard nature; the lower thickness (2 mm) failed to produce the correct stamping shape, but a thickness of (3 mm), closest to the calculated value, succeeded, as shown in Figure 7.

These results support the assumption in cold forging design, making it easier to select sheet metal thickness based on the product shape design (derived from numerical modelling) and the mechanical properties of the metal used.

FIGURE 7. The steel sheet metal products.

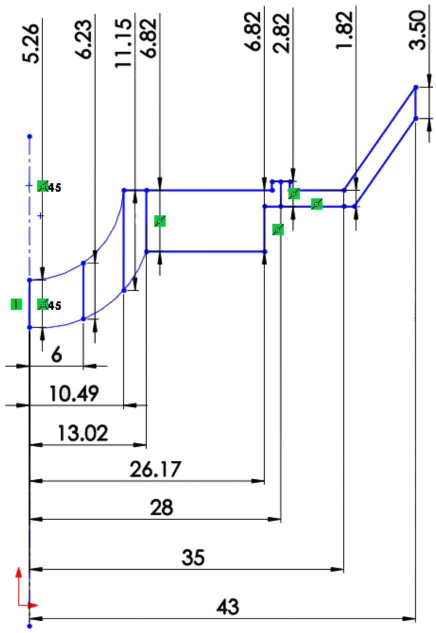


FIGURE 8. The design thicknesses of the product at specific distances.

3. RESULTS AND DISCUSSIONS

In this research, the analysis of forging focuses on the effects of two factors: the thickness of the product and the generated strain.

The discussion of the first factor, thickness, is based on the product design created numerically using Solidworks, aiming to achieve the desired product shape with the design thicknesses, as depicted in Figure 8. This figure presents the cross-sectional thickness of the designed product at specific distances from the centreline, with sections taken at critical locations susceptible to deformation due to the forging process or the complexity of the design. To assess the successfully manufactured products through the cold forging process, the products are cut into two halves, as illustrated in Figures 4–7, and the thicknesses are measured at the same locations identified in Figure 8. The measured thicknesses of the successful products for different types of material are plotted against the design thickness, as shown in Figure 9.

Figure 9 illustrates that lead and aluminium sheet metals closely match the designed thickness, particularly in the central region from the centre of the die profile, with error deviations of 1.14 % and 4.36 %, respectively, as calculated using the error relation formula:

$$\mathrm{err} = \frac{\mathrm{th}_{\max} - \mathrm{th}_{\min}}{\mathrm{th}_{\max}} \times 100\,\%, \qquad (3)$$

where

$\mathrm{th}_{\max}$ is the maximum thickness of the design, or practically measured,

$\mathrm{th}_{\min}$ is the minimum thickness of the design, or practically measured.

This phenomenon occurs due to the height of the upper jaw, which, combined with the softness of the materials, exerts high pressure, pushing the sheet into the lower jaw and resulting in a close thickness up to the middle section of the die jaws profile. It is also noteworthy that the sheet thickness used exceeds the design. However, this high pressure causes the softer materials to flow upwards, increasing the upper part of the product thickness even further, with an error deviation of 62.4 % for lead and 55.69 % for aluminium. This behaviour diminishes when using harder and less soft sheet metals, as observed for brass sheet metal, which exhibits a higher thickness than the design, resulting in a minimum error of 4.94 % and a maximum of 37.33 %. Conversely, the combined effect of hard material with less sheet thickness causes the product thickness to significantly deviate from the design, particularly evident for steel sheet, where the minimum error is 5.73 % and the maximum is 51.73 %. The recorded data of the thicknesses are listed in Table 4.

The second factor to be analysed is the strain of the sheet metal during the forging operation of product manufacturing. The strain calculation is based on the following relation:

$$\varepsilon = \frac{\mathrm{th}_{\mathrm{measured}} - \mathrm{th}_{\mathrm{designed}}}{\mathrm{th}_{\mathrm{designed}}}, \qquad (4)$$

where

t_{measured} is the practically measured thickness of the sheet metals,

t_{designed} is the designed thickness obtained from the numerical modelling.

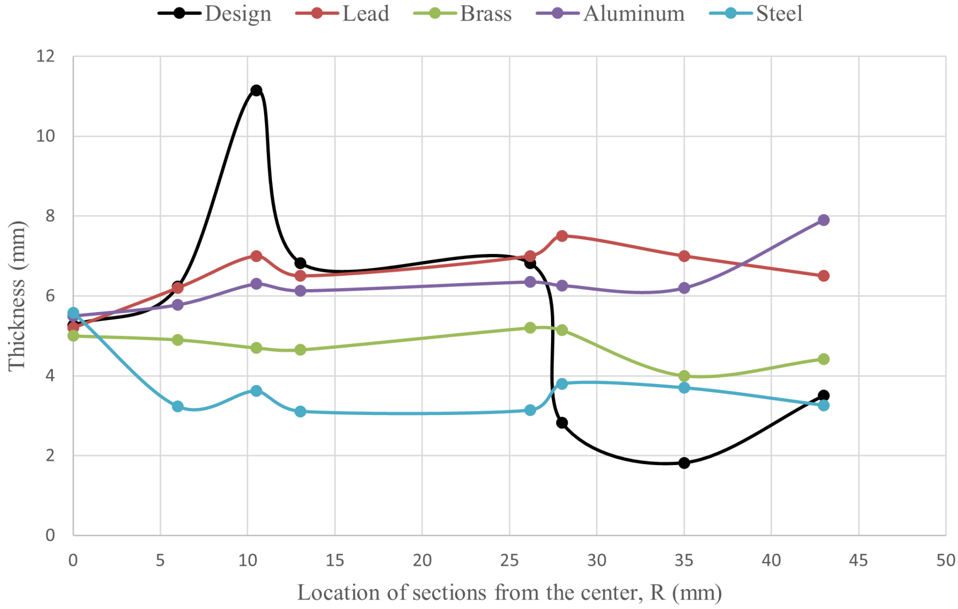


Figure 9. The relation between the design thickness and the measured thicknesses of different metal products.

Location from the center line [mm]	Designed thickness [mm]	Lead product thickness [mm]	Aluminum product thickness [mm]	Brass product thickness [mm]	Steel product thickness [mm]
0	5.26	5.2	5.5	5	5.58
6	6.23	6.2	5.78	4.9	3.23
10.49	7.5	7	6.3	4.7	3.62
13.02	6.82	6.5	6.13	4.65	3.11
26.17	6.82	7	6.35	5.2	3.14
28	2.82	7.5	6.26	5.14	3.8
35	1.82	7	6.2	4	3.7
43	3.5	6.5	7.9	4.42	3.26

Table 4. The recorded thicknesses for the design and different metal products.

The strain results depicted in Figure 10 offer valuable insights into the deformation behaviour of the sheet metal during the cold forging process. It is evident from the figure that all used sheet metals undergo compression strain in the middle region of the die profile from the centre. This phenomenon occurs primarily due to the downward movement of the upper jaw, which exerts pressure on the sheet metal, facilitating the stamping of the product profile. Notably, the brass sheet metal exhibits the highest compression strain among all materials. This can be attributed to its inherent hardness compared to lead and aluminium, as well as the use of a thicker sheet than the design specifications. Conversely, the steel sheet, characterised by its smaller thickness and higher hardness, demonstrates a relatively lower compression strain. However, an interesting observation emerges regarding the outer region of the product profile, particularly beyond 25 mm from the centre. Here, the strain distribution indicates the presence of tensile strains. This occurrence can be attributed to the complex shape of the die profile, which induces deformation and alters material behaviour. The pushing and pressing action of the upper jaw on the sheets lead to material flow, particularly in the softer metals, causing bending in the outer regions of the product profile. This bending results in the development of tensile strains, as depicted in the figure. Overall, the strain analysis provides critical insights into the localised deformation behaviour of the sheet metals, highlighting the influence of material properties and die geometry on the cold forging process.

4. Conclusion

This study has investigated various factors influencing cold forging operations, as revealed through experimental and numerical analyses. The main findings and implications are as follows:

(1.) The assumption used in calculating thickness proved successful in selecting sheet metals closely matching the intended design. This simplifies the process of choosing sheet metal thickness for cold forging based on the product form design model, while considering the ductility properties of the selected metal.

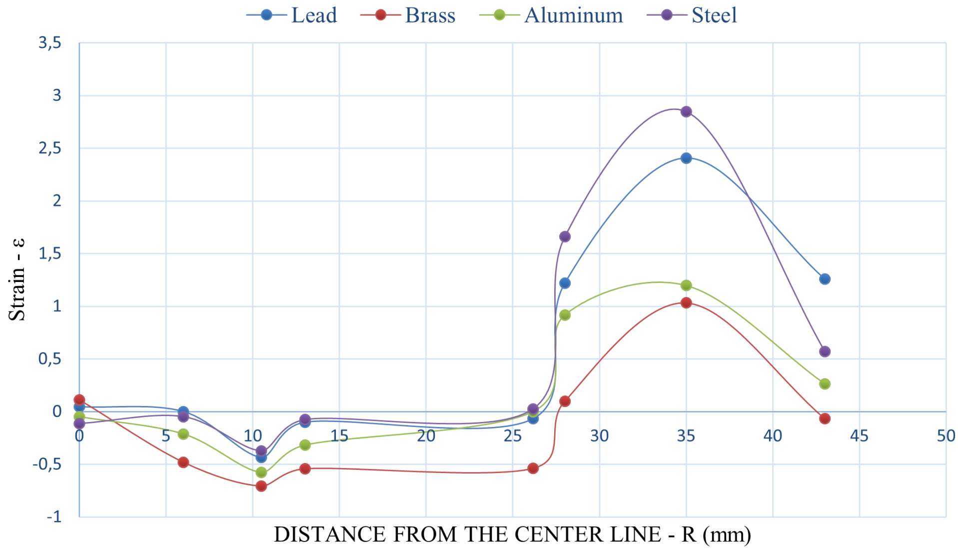


FIGURE 10. The strain effects of the product materials in the cold forging process.

(2.) The choice of sheet metals significantly impacts the final product profile, with softer materials such as lead closely matching the design, followed by aluminium, brass, and steel, which exhibit increasing deviations from the intended profile.

(3.) Lead and aluminium sheet metals closely match the design thickness, particularly in the middle region of the die profile, with error deviations of 1.14 % and 4.36 %, respectively. However, the use of higher sheet thickness than the design, coupled with high pressure, leads to thicker upper product portions, evidenced by error ratios of 62.4 % for lead and 55.69 % for aluminium.

(4.) The deviation from the design diminishes with harder and less soft sheet metals, as seen in the case of brass and steel. Brass, despite having a higher thickness than the design, exhibits a minimum error of about 4.94 % and a maximum error of approximately 37.33 %. Conversely, steel, with its thinner sheet and harder material, has a minimum error of 5.73 % and a maximum error of approximately 51.73 %.

(5.) All sheet metals undergo compression strain in the middle region of the die profile due to the pressing action of the upper jaw during stamping. The degree of compression strain varies, with brass experiencing higher strain due to its hardness and greater thickness, and steel experiencing lower strain due to its thinner sheet and harder material.

In light of these findings, future research endeavours should explore further optimisation strategies for cold forging processes, including the development of advanced modelling techniques to predict material behaviour and optimise product quality. Additionally, investigation into novel materials and innovative die designs could improve the efficiency and effectiveness of cold forging operations in various industrial applications.

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