Enhancing the Energy Efficiency of the Combined Forging Operations of Upsetting and Drawing out

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Abstract. The study investigates the influence of upsetting and drawing out forging parameters on the quality of hook forging and the energy efficiency of these processes. The quality indicators of forged hooks include uneven strain distribution, which leads to a non-uniform distribution of the mechanical properties of the product. The forging technology of hooks was analyzed, and it was determined that the main technological forging operations causing uneven deformation distribution are the sequential upsetting and drawing out processes. Since the influence of specific parameters of these operations remains insufficiently studied, this research was conducted to compare and determine the effect of upsetting and drawing out parameters when performed sequentially in order to improve the mechanical properties of forged hook metal. The modeling was carried out using the QForm engineering software package. To study the distribution of the mechanical properties of the metal, a method for assessing deformation non-uniformity in the cross-section of the forging was applied. Indicators of plastic deformation were considered in one section along the height for upsetting and in one section along the length for drawing out. Additionally, graphs of the deformation non-uniformity coefficient distribution during upsetting and drawing out of the billets were constructed. It was determined that the optimal shape factor for upsetting is h/D = 2. In this case, deformation non-uniformity is reduced by 60%. For drawing out with prior upsetting, the optimal shape factor is also h/D=2 with a strain degree of Ɛ= 20%. The analysis showed that deformation non-uniformity is reduced by 54%. Additionally, the energy efficiency of the processes was analyzed: with h/D=2, energy consumption during upsetting is reduced by 20–25%, and for drawing with h/D=2 and Ɛ= 20%, the third pass (2.838 MN) is the least energy-intensive, providing an energy saving of 25–30%.
Keywords: hook, forging, upsetting, drawing out, shape factor, degree of deformation, quality, energy efficiency.

DOI: https://doi.org/10.52254/1857-0070.2025.2-66-13
UDC: 621.735.623

Îmbunătățirea eficienței energetice a operațiunilor combinate de forjare de bulversare și trefilare

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Razumat. Studiul investighează influența parametrilor de deformare și extragere asupra calității forjarii cu cârlig și a eficienței energetice a acestor procese. Indicatorii de calitate ai cârligelor forjate includ distribuția neuniformă a tensiunii, ceea ce duce la o distribuție neuniformă a proprietăților mecanice ale produsului. A fost analizată tehnologia de forjare a cârligelor și s-a stabilit că principalele operațiuni tehnologice de forjare care provoacă distribuția neuniformă a deformărilor sunt procesele secvenţiale de răsturnare şi extragere. Întrucât influența parametrilor specifici ai acestor operații rămâne insuficient studiată, această cercetare a fost efectuată pentru a compara și determina efectul bulversării și extragerii parametrilor atunci când sunt efectuate secvențial pentru a îmbunătăți proprietățile mecanice ale metalului de cârlig forjat. Modelarea a fost realizată folosind pachetul software de inginerie QForm. Pentru a studia distribuția proprietăților mecanice ale metalului s-a aplicat o metodă de evaluare a neuniformității deformației în secțiunea transversală a forjarii. Indicatorii deformarii plastice au fost luați în considerare într-o secțiune de-a lungul înălțimii pentru răsturnare și într-o secțiune de-a lungul lungimii pentru extragere. În plus, au fost construite grafice ale distribuției coeficientului de neuniformitate de deformare în timpul răsturnării și extragerii ţaglelor. S-a determinat că factorul de formă optim pentru răsturnare este h/D = 2. În acest caz, neuniformitatea deformației este redusă cu 60%. Pentru tragerea cu deformare prealabilă, factorul de formă optim este, de asemenea, h/D=2 cu un grad de deformare de Ɛ=20%. Analiza a arătat că neuniformitatea deformației este redusă cu 54%. În plus, a fost analizată și eficiența energetică a proceselor: cu h/D=2, consumul de energie în timpul bulversării este redus cu 20–25%, iar pentru desen cu h/D=2 și Ɛ=20%, a treia trecere (2,838 MN) este cea mai puțin consumatoare de energie, oferind o economie de energie de 25–30%.
Cuvinte-cheie: cârlig, forjare, răsturnare, extragere, factor de formă, grad de deformare, calitate, eficiență energetică.

Повышение энергоэффективности совместного выполнения кузнечных операций осадки и протяжки

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Аннотация. В работе проведено исследование влияния параметров кузнечных операций осадки и протяжки на качество ковки крюков с повышением энергоэффективности этих процессов. К показателям качества кованых крюков относятся неравномерное распределение деформации, которое обуславливает неравномерное распределение показателей механических свойств изделия. Рассмотрена технология ковки крюков и установлено, что основными технологическими кузнечными операциями, вызывающими неравномерное распределение деформации, являются последовательное выполнение операций осадки и протяжки. При этом влияние конкретных параметров этих операций до сих пор недостаточно изучено. С целью улучшения механических свойств металла кованых крюков проведено исследование для сравнения и определения влияния параметров кузнечных операций осадки и протяжки при их последовательном выполнении. Моделирование выполнено с применением инженерного программного комплекса Qform. Для исследования распределения механических свойств металла использован метод оценки неравномерности деформации металла в сечении поковки. В исследовании приведены параметры моделирования осадки и протяжки. Результаты анализа моделирования рассмотрены в поперечных сечениях поковки на конечной стадии процесса осадки и после третьего прохода процесса протяжки. Были проанализированы показатели пластической деформации в одном сечении по высоте для осадки и в одном сечении по длине для протяжки. Также построены графики распределения коэффициента неравномерности деформации при осадке и протяжке заготовок. Установлено, что для осадки оптимальным вариантом является коэффициент формы с отношением h/D=2. В этом случае неравномерность деформации снижается на 60 %. Для протяжки с предварительной осадкой оптимальным вариантом является коэффициент формы со значением h/D=2 и степенью деформации ε=20 %. Анализ показал, что неравномерность деформации уменьшается на 54 %. Также проведена оценка для повышения энергоэффективности процессов осадки, где энергопотребление при отношении h/D=2 снижается на 20–25 %, и протяжки, где режим h/D=2, ε=20 % является наименее нагруженным на третьем проходе (2,838 МН), что обеспечивает экономию энергии на 25–30 %.

Ключевые слова: крюк, ковка, осадка, протяжка, фактор формы, степень деформации, качество, энергоэффективность.

INTRODUCTION

The quality of forgings remains a consistently relevant issue in the study of metal-forming technologies.

Heavy-duty forged hooks are no exception, as they are frequently used as key components in lifting equipment within the energy sector — particularly in the installation of wind turbines, hydroelectric power stations, and the transportation of heavy structures.

Optimizing forging operations such as upsetting and drawing out not only enhances the reliability and safety of these components but also reduces energy consumption in production processes, which is a crucial aspect of sustainable development and industrial energy efficiency.

The process of manufacturing hooks through forging is complex, as the final product must meet a number of requirements: high strength, hardness, impact toughness, and plasticity. Plasticity is especially important in this context because, in the event of overload, the hook must be able to deform to warn the user of potential failure or malfunction. These properties ensure the reliability and safety of hook operation.

It has been established that the quality of hook forging is largely determined by the sequential execution of upsetting and drawing-out operations. Therefore, it is relevant to conduct a study aimed at identifying which specific parameters of these forging operations influence the quality of forgings for critical applications, particularly hooks.

Numerous works have been devoted to the study of the design and shape of a forged hook, the choice of material for its improvement, the improvement of strength, and the reduction of maximum stress, using modeling and the finite element method. In [1], the aim of the study was to model and modify the shape of the hook to reduce the maximum stress caused by the load. The design of the mold concerned both the longitudinal section of the hook and the cross-sectional shape. The study confirmed that the trapezoidal cross-section proposed in the literature corresponds to a reduced maximum stress. The new result of the study of the T-shaped cross-section of the hook showed better results than the trapezoidal cross-section. The authors of

[2] say the opposite; they determined the most effective hook cross-section among five different geometric profiles. The observed cross-sectional shapes were rectangular, circular, trapezoidal, T-shaped, and I-shaped. The study was carried out using SolidWorks software and finite element analysis. The results of the study indicate that the trapezoidal cross-section hook showed better performance and a higher safety factor. Improving the hook design leads to a reduction in the likelihood of breakage and undesirable incidents. Similarly, the authors of [3] analyzed the hook for five different cross-sections, namely triangular, rectangular, trapezoidal, circular and cavernous. The authors used SolidWorks 2019 software to design the hooks with the different five cross-sections, and ANSYS Workbench was used for the stress-strain analysis. The analysis showed that hooks with a trapezoidal cross-section are stronger than the other four cross-sections and have a greater ability to absorb and retain the deflection caused by vertical loading. To analyze the strength of the hook (with a trapezoidal cross-section), the authors of [4] used two methods: the first method is an analytical calculation, and the second method is a finite element method (FEM), which was performed in the ANSYS software. After obtaining the results of the analytical calculation and FEM analysis, the authors concluded that the total stresses determined by the analytical calculation were 9.8 % lower than the stresses obtained from the ANSYS software. To increase the strength of the hook, the authors of [5] performed a mechanical study of a hook using AISI 4340 alloy steel with different vanadium contents. The analysis showed that AISI 4340 alloy steels with 0.05% vanadium create a fine grain structure that improves mechanical properties. The authors concluded that the use of 99.95% AISI 4340 alloy steel with 0.05% vanadium provides high hook strength and ensures reliability and stability when moving heavy loads. The authors of [6] analyzed and designed hooks made of different materials, such as structural steel, ASTM G 60 (gray cast iron), and high-strength low-alloy steel. The authors used CATIA software to build a 3D model of the hook and ANSYS software to determine the stresses that occur in it. The research results showed that high-strength steel produces minimal stresses, and therefore it is possible to increase the service life of the hook and reduce fracture stresses. To test the strength and stability of the materials (AISI G 60, vanadium steel, carbon steel 1018 and Income 718) of the hook, the authors [7] used CATIA software to design a hook with a lifting capacity of 63,000 kg. The study was carried out using static, vibration and harmonic analyses. After considering all the results, the Inconel 718 material using the modified model 2 showed better performance compared to other materials and models. Also, for hook fabrication and material selection, the author of [8] similarly performed fatigue analysis of hooks made of different materials such as structural steel, wrought iron, and aluminum alloy using FEA (ANSYS) finite element software. The results showed that structural steel and wrought iron produced the lowest stresses. Further fatigue analysis of these two materials revealed that wrought iron can withstand the maximum number of fatigue cycles before failure. Therefore, the author recommends using forged iron for the manufacture of the hook. The author of [9] conducted a study to increase the productivity of the hook forging process at an enterprise. This work is devoted to the study of the time and movement of hook production in forging, finding the optimal cycle time and the most efficient way to use the available resources, which include materials, equipment, people and money. The author found that productivity gains in hook production could be increased in percentage terms by 107% after proper implementation of motion and time studies.

Forging is a process of metal pressure treatment that forms a metal part by applying a force load to it during deformation on universal equipment using forging operations. The main advantage of forging compared to other methods (casting or machining) of manufacturing metal products is that forging improves the mechanical properties of the metal, making it stronger and more ductile and improving its grain structure. The author of [10] highlighted the advantages of the metal forging process in his section. The study [11] analyzes recent advancements in the field of forging, noting that modern forging plays an important role in contemporary industry and has undergone substantial technological development. The author also found out that modern forging has less chance of defects and the ability to forge larger forgings, which was not possible before. The authors of [12] conducted a review of forging processes and the associated defects, discussing their causes and possible methods of elimination. To investigate the causes of such defects, the authors used a fishbone diagram. The authors concluded that a part made by forging is of better quality than a part made by another method.

It has been found that the main technological processes of hook forging that ensure high mechanical quality indicators in their production are forging operations of upsetting and drawing out. Similarly, the authors of [13] believe that the quality of forgings depends on the processes of upsetting and drawing out. The authors proposed methods to improve the quality of forgings and are confident that this is undoubtedly of great importance. To improve the quality of large forgings, the authors of [14] proposed a forging method that involves depositing billets with concave faces. This study was conducted using the finite element method. The depth of the concave faces of the billet was the main research parameter. The results of this study showed that the proposed forging method, which consists in depositing billets with concave faces, showed high efficiency for improving the quality of forgings. The authors of [15] studied a new method of forging large ingots based on the upsetting of billets with conical protrusions. The authors found that the upsetting of a billet with conical protrusions leads to a uniform distribution of deformation in the billet volume. The recommendations were experimentally tested and subsequently confirmed through finite element modeling. The research results were implemented in industry. In order to improve the quality of large forgings, the authors of [16] studied the forging of the double-upsetting process and the drawing-out process and analyzed the defect control mechanism for eliminating internal voids. The results showed that it is possible to eliminate internal voids by using a two-step upsetting process and a subsequent broaching process. To improve the process of drawing out and forging large forgings with flat strikes, the authors of [17] conducted a study using finite element modeling. The results of the study showed an optimized value of the relative feed of the strikers, which can ensure a uniform distribution of metal deformation in the forging. A similar study of the metal drawing out process was conducted in [18] to improve the homogeneity of metal deformation and stress distribution. The author recommends paying attention to the parameter of the degree of strain during drawing out to improve the uniform distribution of strains and stresses. The authors of [19] analyzed the numerical modeling of the forging operation of drawing out using asymmetric strikers. The results of the analysis showed that drawing out billets with asymmetric strikes provides better quality forgings compared to other types of strikes. As reported in [20], an experimental study was conducted on the distribution of deformations and stresses in the billet under various modes of drawing out using a combination of axial and radial strikes. The results of the experimental study determined that at fixed values of the angle of rotation and an increase in compression, it leads to an increase in the values of the average strain intensity and a decrease in the values of the hardness coefficients of the stress-strain diagram.

An analysis of the available literature has shown that there are a considerable number of studies dedicated to the optimal hook shape and the use of various materials for its manufacturing. However, significantly less attention is devoted to examining the direct impact of forging operations on product quality. Most existing studies focus on the control of final operations, whereas the influence of key forging processes — such as upsetting and drawing out — on the quality of forged hooks remains underexplored.

At the same time, the sequential execution of upsetting and drawing out operations, possible options for their combination, and their impact on the quality of the final product - the forged hook - remain insufficiently explored. In this context, special attention should be paid to the strain distribution during their sequential execution, as it largely determines the quality of the forged hook. Therefore, the investigation of this issue represents the primary objective of the present study.

METHODS AND MATERIALS

Hook forging technology is a complex process, so let's take a closer look at the specifics of hook forging technology (Fig. 1). The first operation is ingot billeting, which involves knocking down the edges and removing the taper, thus turning the ingot into a billet. The ticketing process also includes forging a trunnion to fit the manipulator chuck (to hold the ingot in the chuck or grip the manipulator) and chopping the bottom of the ingot. The next operation is upsetting, during which the process of increasing the transverse dimensions of the billet occurs by reducing its height. In this case, upsetting is used as an operation to improve the mechanical properties of the product and eliminate the cast dendritic structure of the ingot. Next, the drawing-out operation is used, and during this process the length of the billet increases by reducing its cross-section. Then, after drawing out the billet to the appropriate diameter, the process of forging the hook billet of the desired shape and size occurs. After forging the billet, the following bending operation is applied. During this process, the hook billet is given a bent shape according to a given contour; the bending of the billet consists of two parts.(Fig. 1)

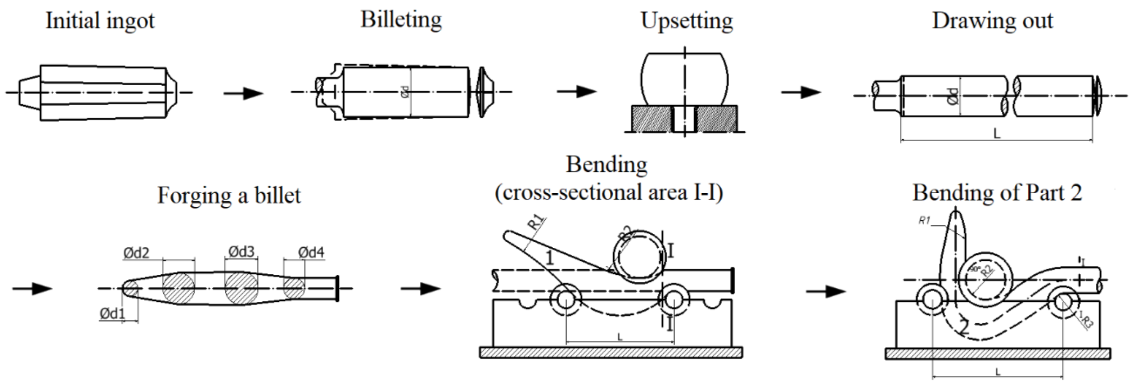


Fig. 1. Hook forging technology scheme.

The quality indicators of forged hooks include strength, hardness, ductility, and impact strength. Strength is required to ensure that the hook does not break under the action of external forces. Hardness is necessary to resist the penetration of other solid bodies under load. Ductility allows the hook to deform in case of overload, serving as a warning sign of potential catastrophic failure. Impact strength is essential for the hook to withstand fracture under repeated loading. These quality indicators characterize the mechanical properties of the material. Most of them depend on the deformation mode applied during forging.

Having analyzed the hook forging technology, it was determined that two key technological forging operations — upsetting and drawing out — are used to improve the mechanical properties of the hook material. Their sequential application ensures the formation of quality in forged hooks, where the maximum deformation occurs. This is critical for breaking down the cast structure of the ingot and achieving a uniform distribution of mechanical properties throughout the billet volume.

At present, the influence of factors on the quality formation of forged hooks remains unexplored — it is still unknown which specific parameters of upsetting and drawing out affect the quality of hook forging. Therefore, a study has been proposed to compare and determine the effect of upsetting and drawing out parameters when performed sequentially, with the aim of improving the quality of forged hooks. Additionally, an analysis of the energy efficiency of the upsetting and drawing-out processes is to be conducted to ensure energy savings in hook manufacturing. To investigate the distribution of deformation indicators during the forging of hooks, a method for evaluating metal deformation non-uniformity in the cross-section of the forging was applied [21]. Computer modeling of the upsetting and drawing-out processes was performed using professional engineering software QForm [22].

The parameters set for the upsetting process modeling were as follows:

1) billet material: Steel 1020;
2) billet diameter: 470 mm;
3) billet temperature: 1150 °C;
4) shape factor (ratio of height h to diameter D): h/D = 1 and h/D = 2 (see Fig. 2);
5) degree of deformation during upsetting: 50%;
6) Upsetting tool: flat dies;

For the drawing-out process, the simulation was based on the following setup:

1) drawing out scheme: lengthwise;
2) rotation angle: 15º;
3) degree of deformation per pass: 10% and 20%;
4) relative feed: 0.5;
5) drawing out tool: flat dies (width: 400 mm, length: 1000 mm, height: 500 mm).

Two upsetting processes followed by four variants of the drawing-out process were simulated (see Fig. 3). The upsetting simulations were conducted under identical deformation degrees of 50% but with different billet shape factors: h/D=1 and h/D=2. Specifically, the first billet had a height of 470 mm, and the second—940 mm. The resulting upset billets were then used as initial billets for two drawing out simulations, where the shape factors (h/D=1 and h/D=2) remained unchanged, and the total deformation per pass during drawing out was 10%. For comparison, two additional drawing-out simulations were carried out, this time increasing the deformation per pass to 20%.

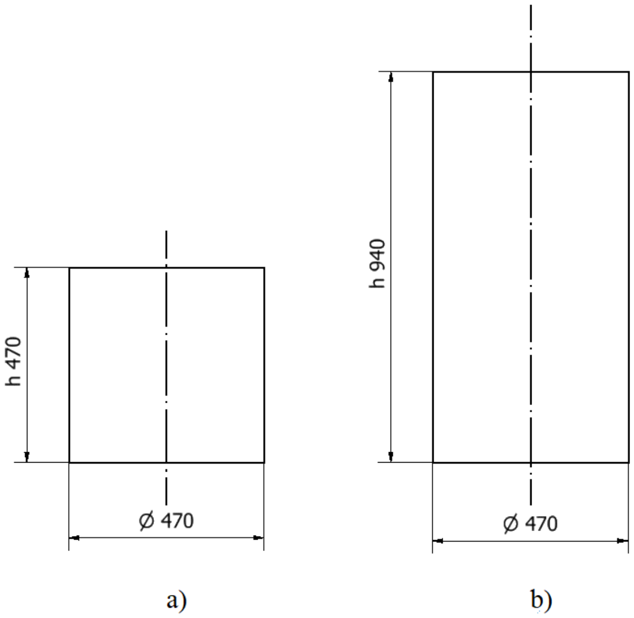


Fig. 2. Sketches of initial billets for upsetting with shape factors: h/D = 1 (a) and h/D = 2 (b)

The simulation results were analyzed in the cross-sections of the forging at the final stage of the upsetting process and after the third pass of the drawing-out process. Plastic deformation indicators were examined in a single cross-section along the height of the billet for upsetting and in a single cross-section along its length for drawing out.

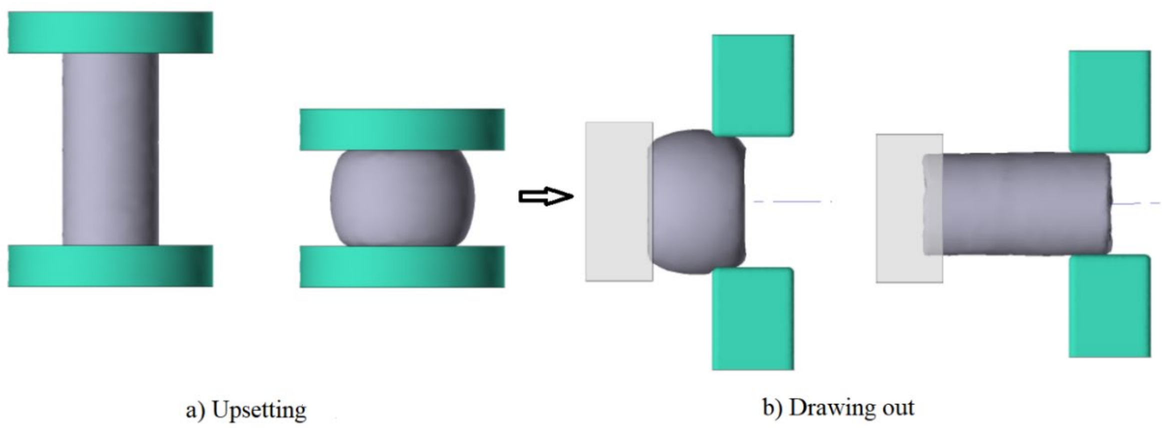


Fig. 3. 3D model of the upsetting process (a) followed by the drawing-out process (b).

To assess the non-uniformity of strain distribution, the strain non-uniformity coefficient C_n was calculated. This coefficient characterizes the degree of uniformity in the distribution of equivalent strain values across the cross-section. The equivalent strain is normalized by the maximum value in the cross-section and therefore cannot exceed one. Four radial lines were constructed in each cross-section, spaced 45º apart. Seven control points were marked on each line, symmetrically with respect to both the point of maximum strain and the center of the cross-section (see Figs. 4 and 5).

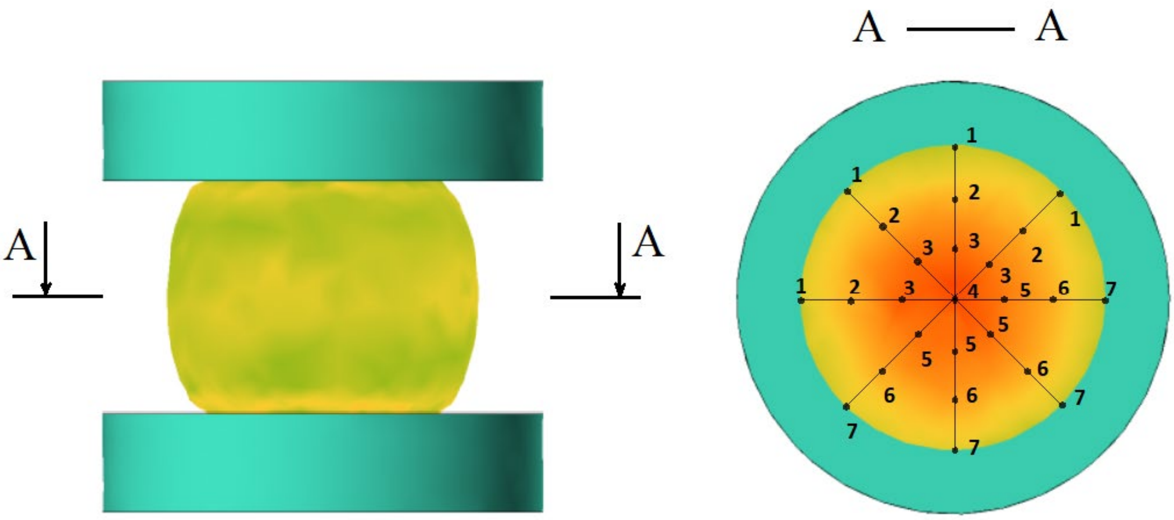


Fig. 4. Schematic representation of lines and control points in the cross-section of the billet during the upsetting process.

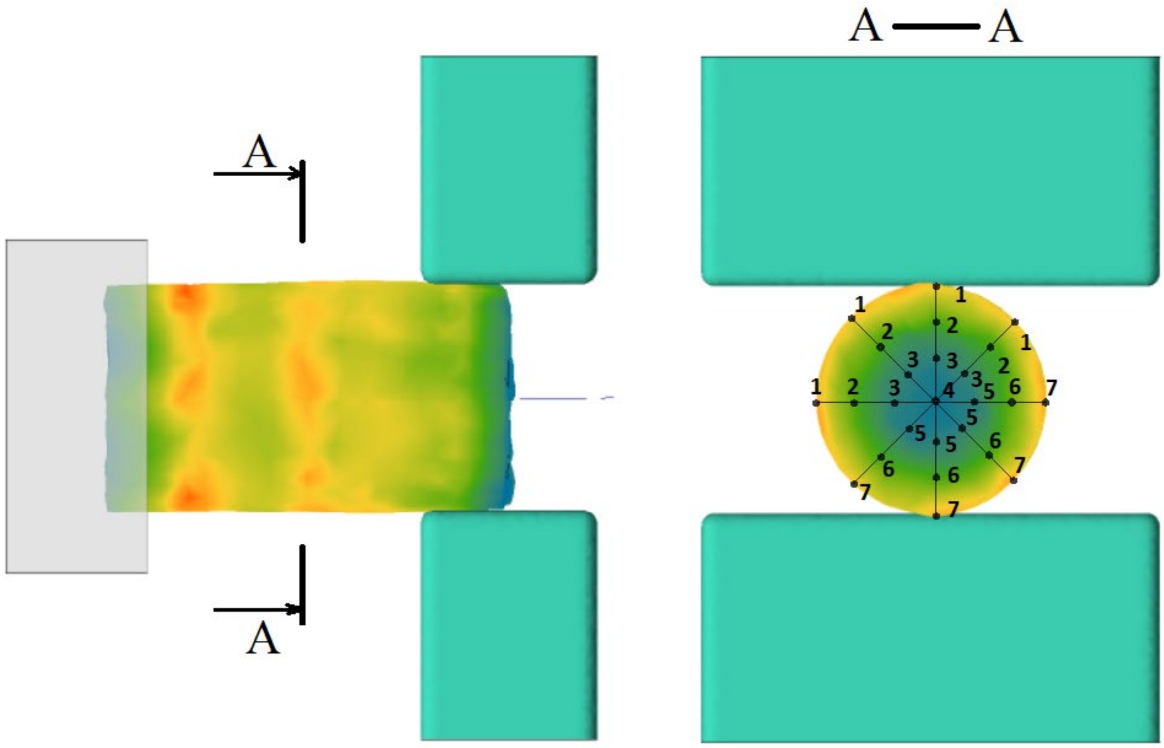
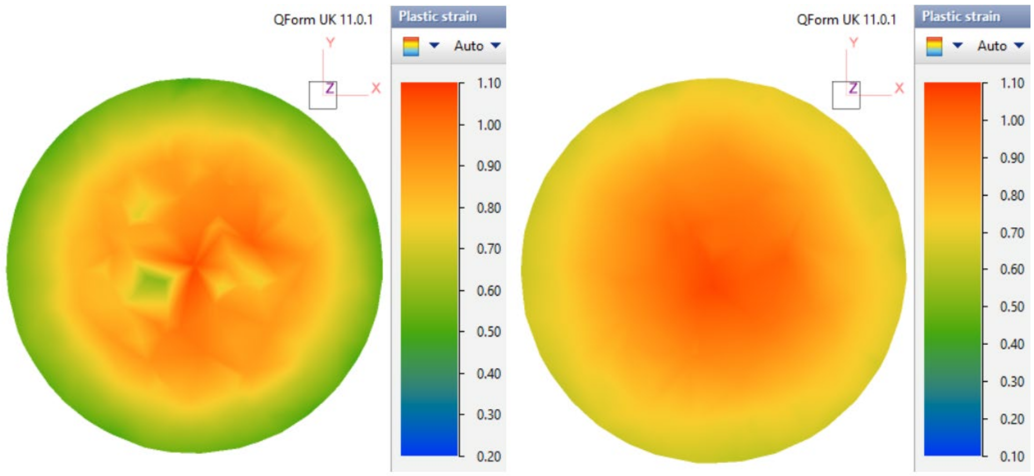


Fig. 5. Schematic arrangement of lines and control points in the cross-section of the billet during the drawing-out process.

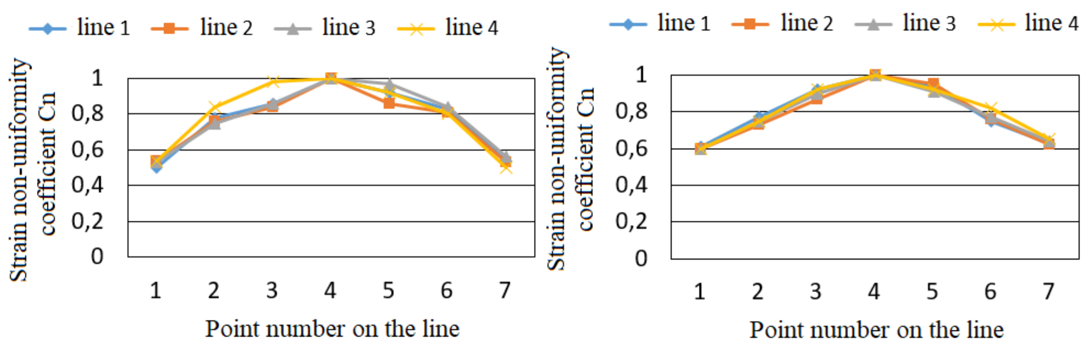


a) b)

Fig. 6. Distribution of plastic deformation in the cross-section during billet upsetting: shape factor h/D = 1, strain ε = 50% (a); shape factor h/D = 2, strain ε = 50% (b).

RESULTS

Figure 6 shows the distribution of strains in the mid-cross-section of the billets during upsetting. It can be seen from Fig. 6 that the degree of deformation and the shape factor have a significant influence on the uniformity of strain distribution and the values of plastic deformation indicatorsFigure 7 presents the graphs of the distribution of the strain non-uniformity coefficient during upsetting of billets with a shape factor of h/D = 1 and h/D = 2.



a) b)

Fig. 7. Graphs showing the distribution of the deformation non-uniformity coefficient during billet upsetting: shape factor h/D = 1 (a), and h/D = 2 (b).

The graphs presented in Fig. 7a show that during the upsetting of a billet with a shape factor of h/D=1, the deformation non-uniformity coefficient decreased by 50%. Figure 7b illustrates that for a billet with a shape factor of h/D = 2, the deformation non-uniformity coefficient decreased by 60%.

Based on the research results, it can be concluded that the optimal option is the shape factor with a ratio of h/D=2 rather than h/D=1. Firstly, this is due to higher values of plastic deformation indicators, as shown in Figure 6b. Secondly, the analysis of the deformation non-uniformity distribution graphs (Fig. 7b) also supports this finding, indicating that the billet with a shape factor of h/D=2 provides a more rational configuration. In this case, the deformation distribution across the section is more uniform, and the non-uniformity coefficient values are closer to one, which indicates more homogeneous deformation. In this case, the deformation non-uniformity is reduced by 60%.

Figure 8 shows the distribution of deformation in the cross-section at the center of billets with shape factors h/D=1 and h/D=2 and different deformation degrees of 10% and 20%, after the third drawing-out pass with prior upsetting of the billets. The simulation results demonstrated that the highest value of plastic deformation is presented in Figure 8d, and the most optimal case is a shape factor of h/D=2 with a deformation degree of 20%.

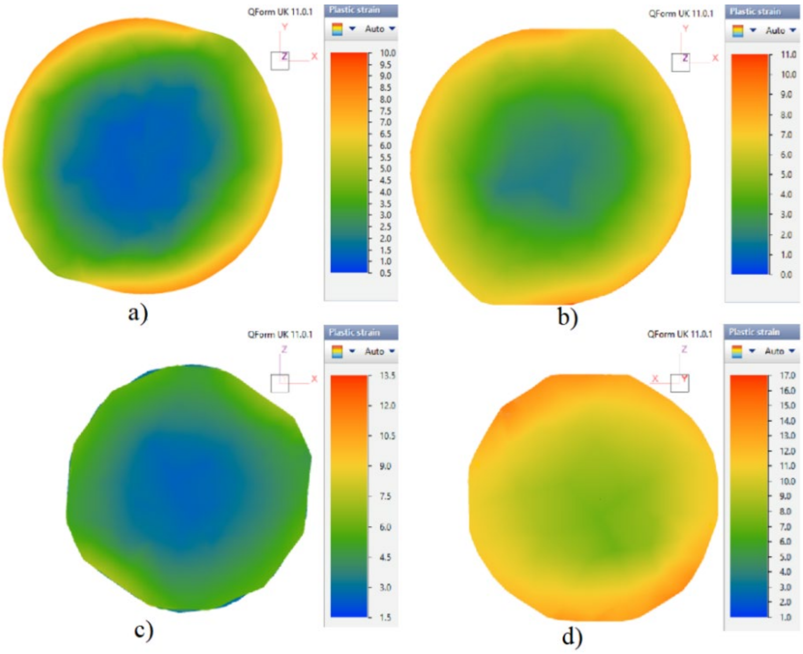


Fig. 8. Distribution of plastic deformation in the cross-section during drawing out of billets after the third pass: h/D = 1, ε=10% (a); h/D = 2, ε =10% (b); h/D =1, ε =20% (c); h/D =2, ε =20% (d).

Using the graphs shown in Fig. 9, it is possible to perform a more detailed analysis of the deformation non-uniformity indicators in the cross-section during drawing out after the third pass.

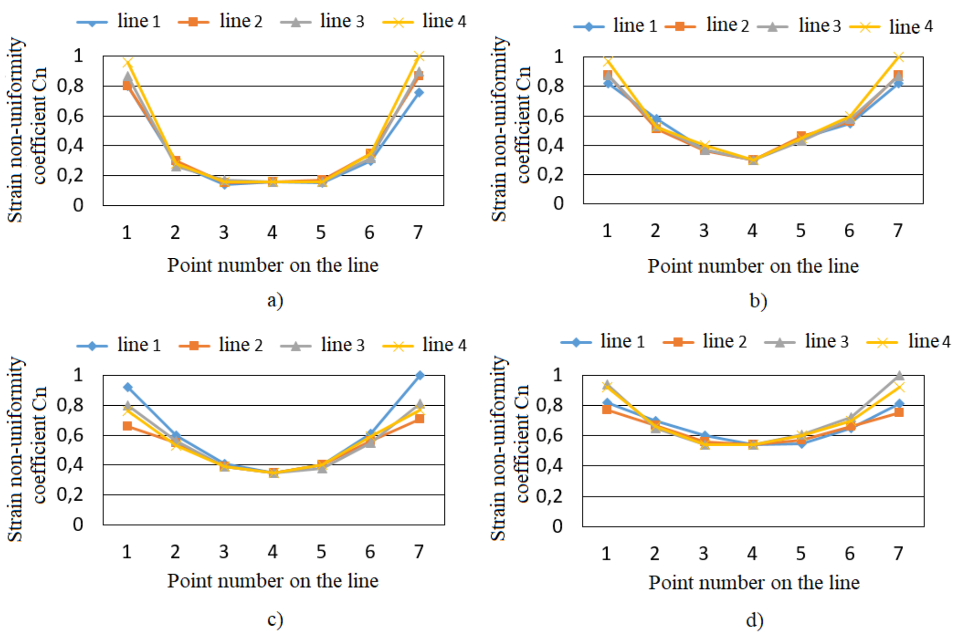


Fig. 9. Graphs of the distribution of the deformation non-uniformity coefficient during drawing out of billets after the third pass: h/D = 1, ε=10% (a); h/D = 2, ε =10% (b); h/D =1, ε =20% (c); h/D =2, ε =20% (d).

As seen in Figure 9a, the deformation non-uniformity coefficient during the drawing out of the billet after the third pass with a shape factor of h/D = 1 and a deformation degree of Ɛ = 10% decreased by 16%. Furthermore, in Figure 9b, the value of the deformation non-uniformity indicator during drawing out with a shape factor of h/D=2 and Ɛ=10% shows a 30% reduction in the non-uniformity coefficient. In Figure 9c, the value of the deformation non-uniformity coefficient during drawing out with h/D=1 and Ɛ=20% decreased by 35%. According to Figure 9d, during drawing out with a shape factor of h/D=2 and a deformation degree of Ɛ=20%, the deformation non-uniformity coefficient was reduced by 54%.

The results of determining the distribution of deformation non-uniformity during the combined execution of upsetting and drawing out, as well as their integration, show that increasing the deformation degree and the shape factor leads to improved deformation distribution uniformity in the forging. In this case, the deformation became 54% more uniform compared to the initial state.

To assess the energy efficiency of the upsetting process, the dependence of the deformation force on the upper plate over time was analyzed using data obtained from QForm (Table 1). Figure 10 presents the graphs showing the relationship between deformation force and time for two upsetting processes: (a) h/D=1 and (b) h/D=2 (Ɛ=50%).

Table 1.

Energy parameters of upsetting

Parameters	Maximum force value, MN	Process time, s	Deformation work, MJ
h/D=1, Ɛ=50%	21,97	1,6	2,9
h/D=2, Ɛ=50%	16,84	3,3	4,8

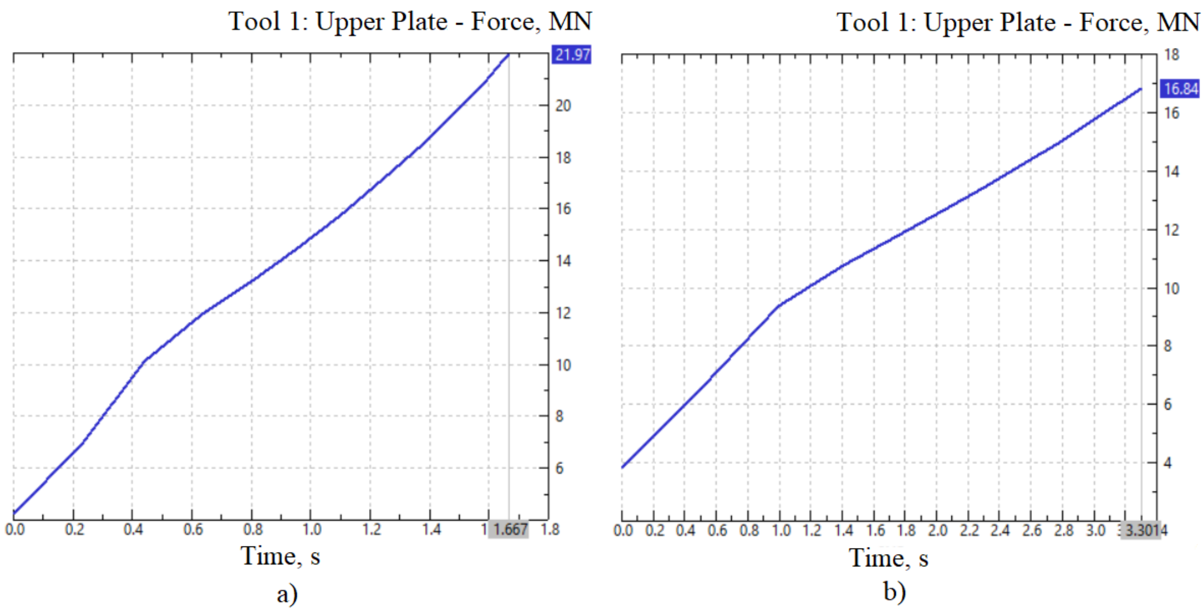


Fig. 10. Graphs of the deformation force versus time for two upsetting processes: (a) h/D=1 and (b) h/D=2 (Ɛ= 50%).

As shown in Figure 10a, for h/D = 1, the maximum force value reaches 21.97 MN, achieved at 1.667 seconds, whereas in Fig. 10b, for h/D = 2, the maximum force decreases to 16.84 MN at 3.3014 seconds. The 23.4% reduction in maximum force for h/D=2 confirms that applying a shape factor of h/D=2 is more energy-efficient and reduces the load on the press, contributing to energy savings. A preliminary calculation of deformation work shows that for h/D=2, energy consumption may be 20–25% lower compared to h/D=1.

To assess the energy efficiency of the drawing-out process, the dependence of the upper die deformation force on time was analyzed using data obtained from QForm (Table 2). The analysis covers one compression stroke of the upper die during the third pass of four drawing-out processes, and graphs of the deformation force versus time were constructed (Fig. 11).

Table 2.

Energy parameters of drawing out

Parameters	Maximum force value, MN	Compression time, s	Deformation work, MJ
h/D=1, Ɛ=1 0%	4,097	1,1	0,106
h/D=1, Ɛ =10%	3,562	0,26	0,032
h/D=2, Ɛ =20%	3,028	0,46	0,032
h/D=2, Ɛ =20%	2,838	0,53	0,026

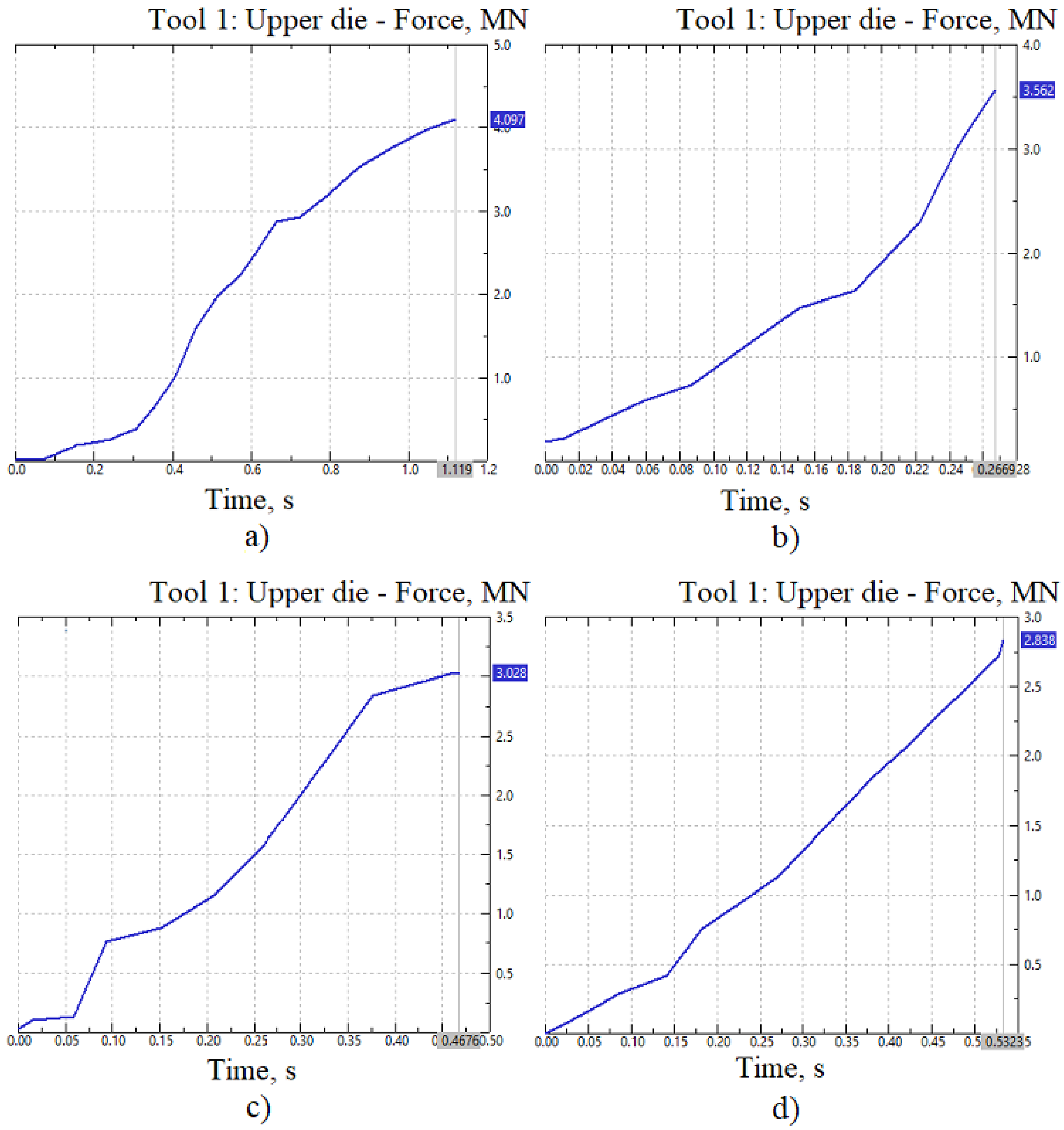


Fig. 10. Graphs of deformation force versus time for four drawing-out processes: (a) h/D=1, Ɛ =10%; (b) h/D=2, Ɛ =10%; (c) h/D=1, Ɛ =20%; (d) h/D=2, Ɛ =20%.

Figure 11 details the deformation force of a single compression during the third pass of the drawing-out process: the maximum force ranges from 2.838 MN (h/D=2, Ɛ=20%) to 4.097 MN (h/D=1, Ɛ=10%), with compression times ranging from 0.26 s to 1.1 s. The mode h/D=2, Ɛ=20% is the least energy-intensive during the third pass (2.838 MN), which is 30.7% lower compared to h/D=1, Ɛ=10% (4.097 MN), ensuring energy savings of 25–30% for this pass. These results are particularly significant for the production of hooks used in the energy industry, especially in cranes for the installation of wind turbines and hydroelectric power plants, where energy efficiency and equipment reliability are critical.

CONCLUSION

It has been determined that the quality of forged hooks is primarily influenced by two forging operations — upsetting and drawing out — as well as the sequence in which they are performed. To improve their quality, a study was conducted to assess the impact of forging parameters upsetting, drawing out, and their combination on the uniformity of deformation distribution during hook production. The process of upsetting followed by drawing out of the billet was simulated, and a method for evaluating deformation non-uniformity in the cross-section of the forging was applied. The simulation demonstrated that the key parameters affecting hook quality are the billet shape factor (h/D) during upsetting and the total strain per pass (Ɛ) during drawing out.

For upsetting, the optimal option is a shape factor with a ratio of h/D=2 rather than h/D=1. Firstly, this results in higher values of plastic deformation indicators, as shown in Fig. 6. Secondly, the analysis of the deformation non-uniformity graphs (Fig. 7) also confirms this research finding, indicating that the billet with a shape factor of h/D=2 (Fig. 7b) is the more rational choice, as it leads to lower deformation non-uniformity in the cross-section. In this case, the deformation non-uniformity is reduced by 60%. For drawing out with preliminary upsetting, the most rational configuration is a shape factor of h/D=2 and a deformation degree of Ɛ=20%, which ensures a 54% reduction in deformation non-uniformity (Fig. 9d). From an energy perspective, the upsetting process with h/D=2 reduces the maximum force by 23.4% and confirms that using a shape factor of h/D=2 is more energy-efficient and reduces the load on the press, contributing to energy savings. A preliminary calculation of deformation work shows that for h/D=2, energy consumption may be 20–25% lower than for h/D=1. In the drawing-out process, the mode h/D=2, Ɛ=20% is the least energy-intensive during the third pass (2.838 MN), which is 30.7% lower compared to h/D=1, Ɛ=10% (4.097 MN), ensuring energy savings of 25–30%.

The outcome of the conducted work is the justification and demonstration of how the execution of upsetting and drawing out operations, when combined, affects the non-uniformity of deformation distribution during the forging of hooks. A key advantage of this study is also the identification of optimal billet parameters during upsetting, followed by sequential drawing out. This combination ensures maximum refinement of the cast structure while maintaining uniform deformation distribution, which in turn improves the quality of the finished forged hooks and reduces energy consumption in manufacturing processes

References

[1] Dumitriu, D., Ionescu, M., Rugina, C. Hook crane shape design improvement for reducing the maximum stress. *Institute of Solid Mechanics of the Romanian Academy, Bucharest, Ro. J. Techn. Sci. – Appl. Mechanics,* 2023, Vol. 68, №1, p. 19-39.

[2] Dipu, N. H., Apu, M. H., Chowdhury, P. P. Identification of the effective crane hook's cross-section by incorporating finite element method and programming language. *Journal Heliyon*, 2024, p. 1-14.

[3] Shrestha, B., Bhandari, A., Poudel, S., Mr. Kasi V. Rao. Crane Hook Analysis for different Cross-Section using ANSYS. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, 2019, Volume 5, Issue 12, December, p. 67-73.

[4] Molnar, D., Blatnicky, M., Dizo, J. Design and strength analysis of crane hook with a 500 kg lifting capacity. *Perner's Contacts,* 2021, 16(2), p. 1-16.

[5] Chandran, V., Manvel Raj, T., Lenin, N., Subramanian, A. Mechanical investigation of crane hook using AISI 4340 alloy steel with various proportions of vanadium. *Journal of Automation and Automobile Engineering,* 2019, Volume 4 Issue 3, p. 1-6.

[6] Mallikarjuna, D. C., Yedukondala, R., Madarsa, S. Design and analysis of crane hook with different materials. *Indo-American Journal of*

Mechanical Engineering, 2019, Vol. 7, Issue 4, p. 1-8.
[7] Venkatesh, S., Raj, M. S., Sarath, V. V. N. Design and strength improvement of the hook with loading capacity of 63000 kg in an open winch drum model by optimizing the materials and the profiles. *Journal of Nonlinear Analysis and Optimization,* 2024, Vol. 15, Issue. 1, №3, p. 183-192.
[8] Zade, M. M., Finite element analysis and fatigue analysis of crane hook with different materials. *International Research Journal of Engineering and Technology, IRJET,* 2017, Volume: 04, Issue: 01, p. 1429-1436.
[9] Prajapati D. R., Productivity improvement of a forging industry using time study technique -a case study. *International Journal of Management, IT and Engineering,* 2014, Volume 4, Issue 12, December, p. 72-84.
[10] Huda, Z. Metal Forging. *In: Metal Forming Processes. Mechanical Engineering Series. Springer, Cham,* 2024, p. 99-120.
[11] Bharti, S., Advancement in forging process: a review. *International Journal of Science and Research,* 2017, Volume 6 Issue 12, December, p. 465-468.
[12] Rathi, M. G., Jakhade N. A. An overview of forging processes with their defects. *International Journal of Scientific and Research*, 2014, Volume 4, Issue 6, June, p. 1-7.
[13] Liu, G. H., Zhuang, Z., Liu, P., Ni, L. Y., Zhu, S. Y., Chen, J. J., Lin, H. C., Liu, L. H. Influence of the blooming process of heavy forgings on the forgings quality. *Advanced Materials Research, Trans Tech Publications Ltd,* 2012, Volumes 538-541, p. 1067-1071.
[14] Markov, O., Zlygoriev, V., Gerasimenko, O., Hrudkina, N., Shevtsov, S. Improving the quality of forgings based on upsetting the workpieces with concave facets. *Eastern European Journal of Enterprise Technologies,* 2018, Volume 5(1), p. 16-24.
[15] Markov, O. E., Khvashchynskyi, A. S., Musorin, A. V., Markova, M. A., Shapoval, A. A., Hrudkina, N. S. Investigation of new method of large ingots forging based on upsetting of workpieces with ledges. *The International Journal of Advanced Manufacturing Technology. Springer,* 2022, Volume 122, p. 1383–1394.
[16] Su, J., Chen, Y., Chen, Y., Shi, Y. (2011). Defect recovery and control in heavy forgings by two times upsetting and stretching process. *Advanced Materials Research,* 2011, Vols. 291-294, p. 706-709.
[17] Chen, K., Yang, Y., Shao, G., Liu, K. Simulation of large forging flat-anvil stretching process and its optimization. *Journal of Shanghai Jiaotong University (Science),* 2011, Volume 16, p. 199-202.
[18] Pop, E. A. Research on stretching by forging. *Scientific Bulletin Series D: Mining, Mineral Processing, Non-Ferrous Metallurgy, Geology & Environmental Engineering*, 2024, Vol. 38, p. 27.
[19] Banaszek, G., Berski, S., Dyja, H. Numerical analysis of the torsion stretch forging operation in asymmetric anvils. *Metallurgical and Mining Industry,* 2011, Vol. 3, No. 7, p. 98-101.
[20] Kukhar, V.V., Vasylevskyi, O.V. Experimental research of distribution of strains and stresses in work-piece at different modes of stretch forging with rotation in combined dies. *Metallurgical and Mining Industry,* 2014, No. 3, p. 71-78.
[21] Chukhlib, V., Ashkelianets, A., Gubskii, S., O. Petrov, O., Duvanskii, O., Palienko, V., Okun, A. Development of a technological concept for designing forging processes taking into account the influence of the deformation mode on the quality of forging pieces. Bulletin of the National Technical University «KhPI». Series: Hydraulic machines and hydraulic units, no 1″2021, p. 95-103.
[22] Qform UK. URL: https://www.qform3d.com/ (accessed January 21, 2025).

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