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Effect of deformation degree during drawing out on the quality of heavy-duty hook forgings

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Вплив ступеня деформації під час витяжки на якість важких поковок з гаком

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Abstract. *This study investigates the influence of the degree of deformation during the drawing out forging operation on the distribution pattern of plastic strain in billets intended for manufacturing high-capacity lifting hooks. The primary objective is to determine the optimal deformation degree that enhances the uniformity of plastic strain distribution across the forging's cross-section. The research was conducted using numerical modeling of the sequential upsetting and drawing out processes, accounting for the continuity of the technological cycle. Drawing out was performed using the "ring" method (circumferential rotation) with a rotation angle of 15° and a relative feed of 0.5. Three deformation degrees per pass were analyzed: 10%, 15%, and 20%. To quantitatively assess strain uniformity, the nonuniformity coefficient C_n was employed, defined as the ratio of equivalent strain values at control points to the maximum equivalent strain within the cross-section. It was established that increasing the deformation degree from 10% to 20% raises the level of accumulated plastic strain and improves its uniformity across the cross-section. The most uniform strain distribution was achieved at a deformation degree of 20%, where the minimum nonuniformity coefficient value was 0.54. This indicates a 46% reduction in strain nonuniformity (since C_n=0.54 corresponds to nonuniformity reduced to 54% of the reference maximum difference). The obtained results can be applied in the development of rational technological regimes for forging high-capacity lifting hooks with enhanced requirements for quality and reliability.*
Keywords: *drawing out, upsetting, degree of deformation, plastic strain, strain nonuniformity coefficient, high-capacity lifting hook forging.*

Анотація. *У цьому дослідженні досліджується вплив ступеня деформації під час операції витяжного кування на характер розподілу пластичної деформації в заготовках, призначених для виготовлення великовантажних вантажопідйомних гаків. Основною метою є визначення оптимального ступеня деформації, який підвищує рівномірність розподілу пластичної деформації по поперечному перерізу поковки. Дослідження проводилося з використанням числового моделювання послідовних процесів висадки та витяжки з урахуванням безперервності технологічного циклу. Витяжка виконувалася методом "кільця" (окружне обертання) з кутом повороту 15° та відносною подачею 0,5. Було проаналізовано три ступені деформації за прохід: 10%, 15% та 20%. Для кількісної оцінки рівномірності деформації використовувався коефіцієнт нерівномірності Cn, який визначається як відношення значень еквівалентної деформації в контрольних точках до максимальної еквівалентної деформації в межах поперечного перерізу. Було встановлено, що збільшення ступеня деформації з 10% до 20% підвищує рівень накопиченої пластичної деформації та покращує її рівномірність по поперечному перерізу. Найбільш рівномірний розподіл деформації був досягнутий при ступені деформації 20%, де мінімальне значення коефіцієнта неоднорідності становило 0,54. Це свідчить про зменшення неоднорідності деформації на 46% (оскільки Cn=0,54 відповідає неоднорідності, зменшеній до 54% від контрольної максимальної різниці). Отримані результати можуть бути застосовані при розробці раціональних технологічних режимів кування високовантажних вантажопідйомних гаків з підвищеними вимогами до якості та надійності.*
Ключові слова: *витяжка, осаджування, ступінь деформації, пластична деформація, коефіцієнт неоднорідності деформації, кування високовантажного вантажопідйомного гака.*

Introduction. High-capacity lifting hooks are critical components in hoisting and transportation systems, operating under variable and impact loads. The operational reliability of such components is determined by a combination of factors, among which the structural homogeneity of the metal, the absence of internal defects, and a favorable orientation of the fibrous structure play a key role. These characteristics are primarily formed during the forging process.

One of the key parameters influencing the formation of the structure and quality of forged products is the pattern of plastic strain distribution throughout the billet volume. Strain nonuniformity can lead to the formation of internal defects and premature failure of the component. For critical parts, particularly high-capacity lifting hooks, achieving uniform deformation penetration (thorough working) of the metal is one of the primary technological challenges.

In the technology for manufacturing single-horn (single-prong) lifting hooks, a combined forming scheme is employed, which includes preliminary upsetting of the billet followed by drawing out [1]. Upsetting ensures the breakdown of the cast structure and a substantial reduction in internal porosity of the metal, while the drawing out operation imparts the required shape and length to the billet, creating a favorable fiber orientation [2, 3]. At the same time, the degree of deformation during drawing out significantly affects the pattern of its distribution throughout the metal volume and can either improve or impair the structural homogeneity of the final product.

Despite the considerable number of studies on metal forming processes, the specific influence of the degree of deformation during drawing out—performed after preliminary upsetting—on the nonuniformity of plastic strain in billets for single-horn high-capacity lifting hooks remains insufficiently explored. Establishing quantitative relationships for the distribution of plastic strain will enable the justification of rational technological forging regimes and improve the quality of the finished products.

Literature Review and Problem. Upsetting is a fundamental operation in the forging of large critical forgings, as it ensures thorough working (penetration) of the metal. This process breaks down the cast structure, heals internal defects, and promotes the formation of a homogeneous microstructure, which is crucial for the strength of the final product. However, as demonstrated by the results in [4], the upsetting process is accompanied by significant nonuniformity in the stress-strain state (SSS), which directly depends on the initial shape of the billet. Furthermore, work [5] has established that the pattern of metal flow is substantially influenced by friction conditions and the temperature-velocity regimes of processing.

Therefore, to achieve uniform strain distribution, it is effective to use billets of special (profiled or contoured) shapes and intensified processing regimes. In particular, work [6] has demonstrated that the application of profiled billets helps to distribute deformation more homogeneously and prevent the formation of internal cracks. Additionally, enhanced quality can be achieved through complex loading schemes. As shown in study [7], the combination of deformations and varying stresses ensures better working (penetration) of the metal structure throughout the entire billet volume. This not only improves its strength but also enables effective control of product quality in open-die forging.

The primary formation of quality and strength in large forgings occurs during the drawing out forging operation. In study [8], based on numerical modeling, it was established that when processing large forgings with flat dies, insufficient working (penetration) of the central zone in the billet's cross-section persists, necessitating improvements in the feed and reduction parameters. The relevance of seeking new technological solutions to enhance the drawing out process is confirmed in work [9], which analyzes modern forging regimes from the perspective of improving metal quality and production energy efficiency.

One of the most interesting approaches to improving metal quality is proposed by the authors of work [10]. They demonstrated that the use of dies with unconventional (asymmetric) shapes induces intense internal twisting of the metal, which significantly enhances the breakdown of coarse structures compared to conventional drawing out. A logical extension of this idea is presented in work [11], where the authors suggested replacing preliminary upsetting with billet profiling using wedge-shaped dies prior to drawing out. According to their findings, this approach enables through-working of the metal, reduces press force requirements, and saves processing time.

In modern practice, combined forging technologies are increasingly employed. For example, as demonstrated in work [12], the application of a double "upsetting–drawing out" cycle represents one of the most effective methods for eliminating internal defects. This combination of operations not only changes the shape of the billet but also enables targeted control over the restoration of the metal microstructure in the core of heavy forgings.

At the same time, improving the forging process—even when using special convex dies—always carries the risk of compromising the integrity of the product. Studies [14, 15] demonstrate that critical stresses arising at high degrees of deformation during drawing out can lead to crack formation.

Thus, the analysis of global experience confirms that achieving high-quality and safe products, such as lifting hooks, requires finding an optimal balance between improving metal working and preserving the structural integrity of the material. This necessitates detailed computer modeling to determine rational degrees of deformation, which constitutes the primary objective of the present work.

Purpose and objectives of the research. The objective of this work is to investigate the influence of the degree of deformation during the drawing-out forging operation—performed after preliminary upsetting of the billet—on the distribution of plastic strain and to evaluate the nonuniformity of deformation throughout the volume of the billet for high-capacity lifting hooks.

Materials and Methods of Research. The object of the study was a cylindrical billet made of steel 1020 (equivalent to Ukrainian grade steel 20), with an initial diameter of 470 mm and height of 940 mm. Steel 1020 is a low-carbon steel commonly used for forging heavy-duty lifting hooks due to its good hot workability, moderate strength, and suitability for subsequent heat treatment.

Numerical simulation of the forging processes was performed using the QForm UK software package [15] based on the finite element method (FEM). The modeling accounted for the sequential continuity of the technological cycle: preliminary upsetting followed by drawing out.

The forging operations (upsetting and drawing out) were simulated under isothermal conditions at a constant temperature of 1150°C. This temperature corresponds to the typical hot forging range for low-carbon steels like 1020/20, ensuring high ductility, low flow stress, and effective deformation without excessive cracking risk.

Upsetting was performed using flat upsetting plates (dies): the lower plate was fixed, while the upper plate moved vertically downward.

The degree of deformation during upsetting was set at 50% reduction of the initial billet height (from 940 mm to 470 mm).

This stage aimed to achieve preliminary deformation penetration (thorough working) of the metal structure prior to the subsequent drawing-out operation, thereby breaking down the initial cast microstructure, closing internal porosity, and promoting overall homogeneity.

The results obtained after the upsetting stage were used as initial conditions for the subsequent modeling of the drawing-out processes. This approach ensured the continuity of the technological process and the accurate reproduction of real forging conditions.

The 3D model of the initial billet, its position between the plates prior to upsetting, and the state after upsetting are presented in Figure 1.

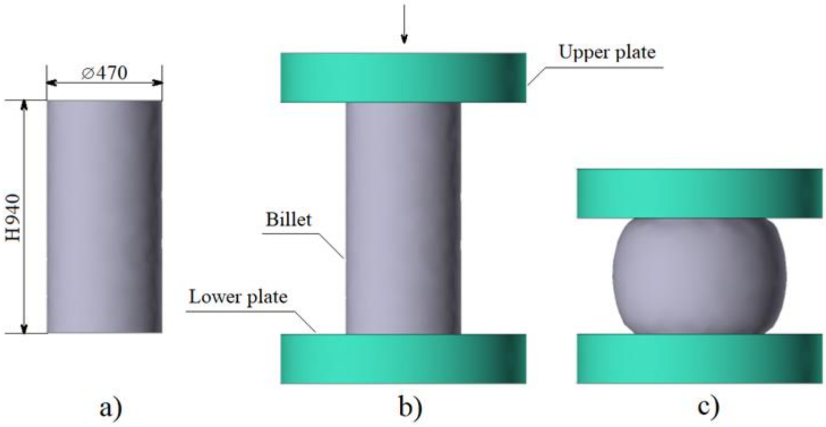

Figure 1 – 3D model of the upsetting operation: (a) initial cylindrical billet (D=470 mm, H=940 mm); (b) billet position before upsetting; (c) billet state after upsetting.

Subsequently, numerical modeling of the drawing-out forging operation was performed. The initial state for this stage was the billet with the already formed distribution of plastic strain obtained after the upsetting stage. This approach ensured the continuity of the technological process and the accurate reproduction of real forging conditions.

The drawing out of the billet was carried out using flat dies with dimensions 400 × 1000 × 500 mm. The "ring" method (circumferential rotation drawing) was selected, which involves sequential reductions of the billet accompanied by rotation (canting) by an angle α = 15°. A relative feed s/h = 0.5 was applied only after a full rotation of the billet (i.e., after completing the 360° circumferential pass).

The schematic diagram and 3D model of the drawing-out process are presented in Figure 2.

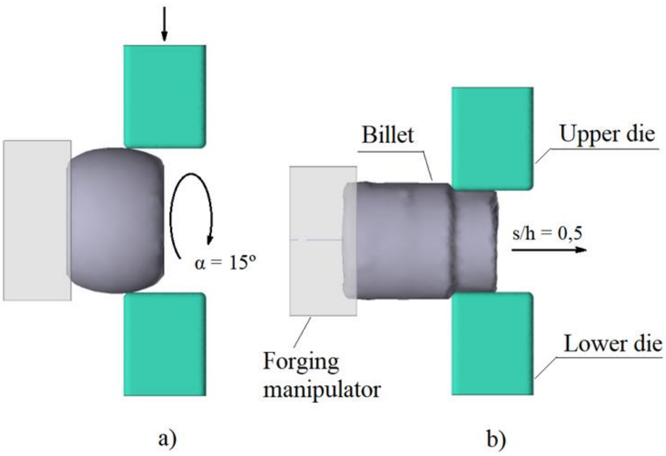

Figure 2 – 3D model of the drawing-out forging operation: (a) initial state of the billet and canting scheme (α = 15°); (b) drawing-out stage and relative feed (s/h = 0.5).

To investigate the influence of the degree of deformation during the drawing-out forging operation on the quality of lifting hook forgings, three modeling variants were performed with different deformation de-

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grees per pass: 10%, 15%, and 20%. For each variant, three sequential drawing-out passes were carried out. After the third pass, the accumulated equivalent plastic strain was determined, and the pattern of its distribution in the cross-section—specifically in the central region of the billet — was analyzed.

This approach enabled the establishment of the relationship between the degree of deformation after the third drawing-out pass and the uniformity of plastic strain distribution. This uniformity is a decisive parameter in ensuring the quality of high-capacity lifting hook forgings.

To evaluate the uniformity of plastic strain distribution, the method for predicting volumetric nonuniformity was applied, with detailed justification provided in work [16]. In each analyzed cross-section, four radial lines were drawn, positioned at 45° angles to one another. Along each line, seven control points were marked, symmetrically arranged relative to the center of the section and the zones of maximum equivalent plastic strain (Figure 3). Within this approach, the nonuniformity coefficient C_n was determined for the strain distribution.

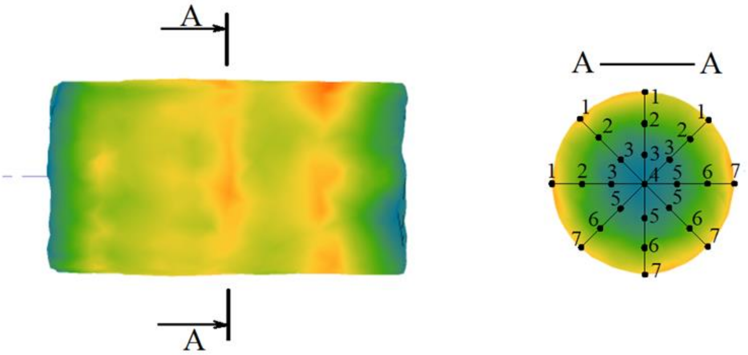

Figure 3 – Schematic of radial lines and control points arrangement in the billet cross-section during drawing out.

The nonuniformity coefficient C_n was calculated as the ratio of the equivalent plastic strain value at each control point in the cross-section to the maximum equivalent plastic strain value within the corresponding cross-section. This definition confines C_n to the range from 0 to 1. Values close to 1 indicate a more uniform distribution of plastic strain across the section.

Figure 4 illustrates the distribution of plastic strain in the central cross-section of the billet after the upsetting stage. The maximum values of plastic strain are concentrated in the central zone, reaching 1, while a gradual decrease is observed toward the surface zone, with minimum values of 0.6. Thus, the range of plastic strain variation across the cross-section is 0.6–1 indicating the presence of nonuniformity in the deformation state.

The plastic strain distribution formed after upsetting determines the initial state of the billet prior to drawing out and influences both the subsequent strain values and the uniformity of its distribution during the drawing-out process.

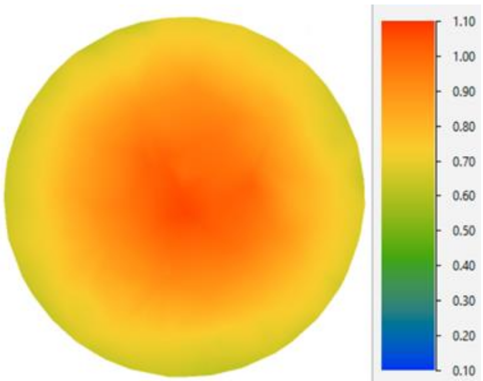

Figure 4 – Distribution of plastic strain in the cross-section of the billet after upsetting.

Figure 5 presents the distribution of plastic strain in the central cross-section of the billet after the third drawing-out pass for deformation degrees per pass of 10%, 15%, and 20%. As can be seen from the contour plots, increasing the deformation degree leads to a more uniform strain distribution across the section, with the most homogeneous pattern observed at 20% (Figure 5c).

At a deformation degree of 10 % per pass (Figure 5a), the plastic strain values vary within the range of 2 to 8, indicating pronounced strain nonuniformity and insufficient working of the central zone.Increasing the deformation degree to 15% (Figure 5b) results in a rise of the minimum strain values to 3.1, while the maximum values remain around 8. This suggests improved deformation penetration in the internal layers of the metal. The most thorough deformation working is observed at a deformation degree of 20% (Figure 5c), where the minimum strain values reach 7.1 and the maximum values attain 13. At this level, the strain distribution along the radius becomes significantly more uniform.

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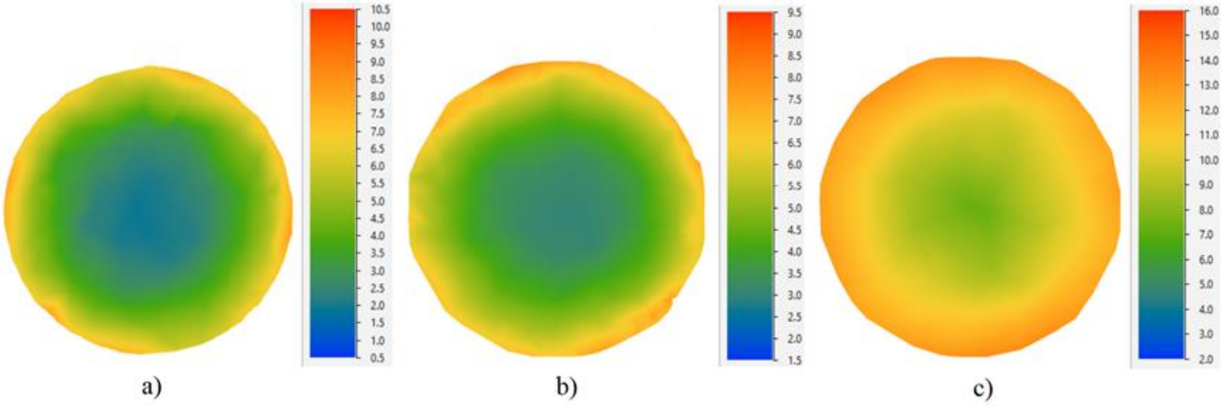

Figure 5. Distribution of plastic strain in the billet cross-section after the third drawing-out pass at different deformation degrees per pass: (a) ε = 10%; (b) ε = 15%; (c) ε = 20%.

The obtained results clearly demonstrate the significant influence of the deformation degree during billet drawing out and confirm the advisability of applying higher deformation degrees to achieve more complete working (penetration) throughout the billet volume. The summarized results of the numerical analysis are presented in Table 1, which includes the minimum and maximum values of plastic strain, as well as the calculated nonuniformity coefficient C_n for each variant of the deformation degree during drawing out.

Table 1. Plastic strain characteristics and nonuniformity coefficient after the third drawing out pass for different deformation degrees per pass.

Deformation degree per pass, ε (%)	Minimum equivalent plastic strain, ε min	Maximum equivalent plastic strain, ε max	Nonuniformity coefficient, C_n
10	2	8	0.25
15	3.1	8	0.38
20	7.1	13	0.54

Figure 6 presents graphs of the nonuniformity coefficient C_n distribution along the measurement lines in the cross-section of billets with different deformation degrees after the third drawing-out pass.

Analysis of the graphs made it possible to establish the pattern of distribution of the deformation nonuniformity coefficient C_n as a function of the billet deformation degree. For all variants, the curves exhibit a characteristic symmetric shape: the maximum C_n values are observed at the outermost (peripheral) points (points 1 and 7), while the minimum values occur in the central zone of the cross-section (points 3–5).

It was established that increasing the deformation degree leads to a rise in the nonuniformity coefficient C_n values in the central zone of the billet. At a deformation degree of 10% per pass (Figure 6a), the minimum C_n value in the central zone is 0.25. When the deformation degree is increased to 15% (Figure 6b), the coefficient rises to 0.38. At a deformation degree of 20% (Figure 6c), the K_n value reaches 0.54.

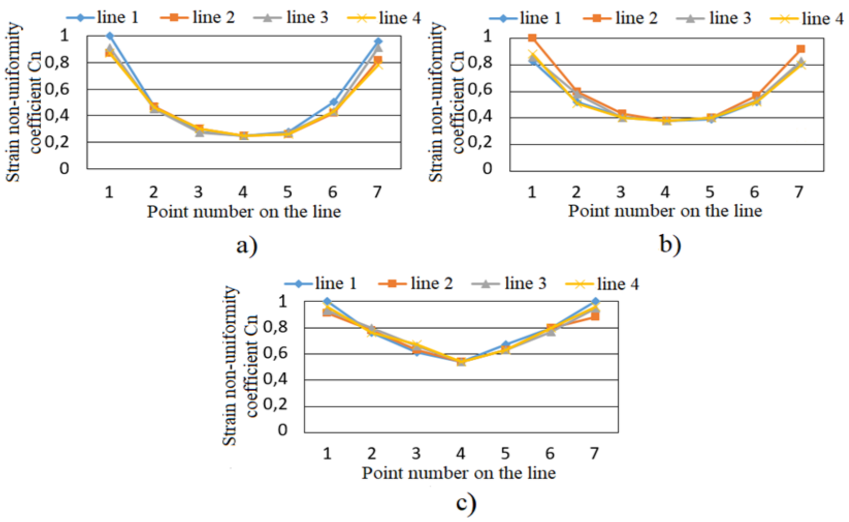

Figure 6. Graphs of the deformation nonuniformity coefficient Cn distribution after the third drawing-out pass for billets with different deformation degrees per pass: (a) ε = 10%; (b) ε = 15%; (c) ε = 20%.

In this case, the billet processed with a deformation degree of 20% per pass (Figure 6c) exhibits the most uniform plastic strain distribution. The minimum value of the nonuniformity coefficient is C_n = 0.54. Since values of the coefficient close to unity correspond to a more uniform strain distribution, the obtained result indicates that the deformation nonuniformity is reduced to 54%.

Conclusions. In this study, numerical modeling of the drawing out processes following preliminary billet upsetting was performed to investigate the influence of the deformation degree in the drawing out forging operation on the pattern of plastic strain distribution and to evaluate deformation nonuniformity throughout the volume of billets intended for high-capacity lifting hooks.

It was established that after upsetting, the billet exhibits nonuniform plastic strain distribution, with values decreasing from the center to the surface within the range of 0.6–1. This initial strain distribution is critical, as it determines the subsequent metal quality and the uniformity of structural working during the drawing-out stage.

The key role of the deformation degree during drawing out has been demonstrated: increasing the deformation per pass from 10% to 20% ensures a transition from pronounced nonuniformity to stable and thorough working of the entire metal volume. In particular, the minimum strain values increase more than threefold (from 2.0 to 7.1).

Analysis of the nonuniformity coefficient C_n confirmed that the central zone of the billet cross-section is the most difficult to deform. However, raising the deformation degree to 20% allows the uniformity in the central zone to increase from 0.25 to 0.54. This result indicates that the deformation nonuniformity is reduced to 54%.

The obtained findings can be used to develop rational technological regimes for open-die forging of high-capacity lifting hooks with enhanced requirements for structural uniformity, mechanical properties, and operational reliability.

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