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OPTIMIZATION OF THE COLD EXTRUSION PROCESS OF SAE 1004 STEEL FOR THE PRODUCTION OF HEXAGONAL FLANGE HEAD SCREWS

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ABSTRACT

Introduction: This study aims to optimize the manufacturing process of hexagonal flange head roofing screws. The fastener is produced in two cold forming stages using SAE 1004 low-carbon steel wires. The addition of a direct extrusion operation to the manufacturing route is proposed, resulting in a 7% reduction in raw material consumption. Analytical and numerical approaches are employed to select the parameters for the extrusion process. The mechanical and metallurgical characterization of the work material is conducted and used as input data for the process analysis approaches. Considering the forming force and the stresses on the tools, the extrusion angle and the matrix casing dimensions were defined. Analytical and numerical results are compared with experimental data. The accuracy of the analyses was validated by a 3% agreement between analytical calculations and numerical simulations. This approach demonstrates the effectiveness of combining methods for process optimization, aiming at sustainability and competitiveness in the fastener industry.

Objective: The study aims to optimize the manufacturing process of hexagonal flange head roofing screws by proposing a new manufacturing route that includes a direct extrusion operation, resulting in a 7% reduction in raw material consumption.

Theoretical Framework: The study is based on analytical and numerical approaches applied to selecting parameters for cold forming processes, considering the mechanical and metallurgical characterization of materials. This foundation enables the integration of analysis and experimentation methods, aiming for efficiency gains, sustainability, and cost reduction in the industrial sector.

Method: The research used SAE 1004 low-carbon steel wires for manufacturing fasteners in two cold forming stages. The new route included the addition of a direct extrusion stage. The mechanical and metallurgical characterization of the material was performed to provide input data for the analyses. Parameters such as forming force, tool stresses, extrusion angle, and matrix casing dimensions were defined based on analytical and numerical analyses.

Results and Discussion: The obtained results demonstrated the effectiveness of the proposal. The forming force and tool behavior were suitable for the new manufacturing route. Comparisons between analytical calculations, numerical simulations, and experiments showed a 3% agreement, proving the precision of the analyses and validating the proposed model. This approach highlights the feasibility of combining analytical and experimental methods to optimize industrial processes.

Research Implications: The research contributes to the fastener industry by demonstrating that process optimization based on integrated methods can enhance sustainability and competitiveness. The reduction in raw material consumption and the application of analytical and numerical tools represent significant advances in efficiency and innovation in manufacturing processes.

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Originality/Value: The study presents an innovative approach by integrating analytical, numerical, and experimental methods to optimize industrial cold forming processes, specifically in screw manufacturing. The originality lies in the inclusion of a direct extrusion operation in the conventional manufacturing route, resulting in a 7% reduction in raw material consumption, a significant advancement for industrial sustainability and efficiency. Moreover, the demonstrated precision among different analysis methods adds value by providing a robust and applicable solution for the fastener industry, contributing to more sustainable and competitive practices.

Keywords: Analytical Analysis, Direct Extrusion, Finite Element Analysis, Forging.

OTIMIZAÇÃO NO PROCESSO DE EXTRUSÃO A FRIO DO AÇO SAE 1004 PARA OBTENÇÃO DE PARAFUSO SEXTAVADO FLANGEADO

RESUMO

Introdução: Este trabalho tem como objetivo otimizar o processo de fabricação de parafusos telheiros com cabeça sextavada flangeada. O fixador é produzido em duas etapas de conformação a frio a partir de arames do aço baixo carbono SAE 1004. A adição de uma operação de extrusão direta a rota de fabricação é proposta resultando em uma redução de 7% no consumo de matéria-prima. Abordagens analíticas e numéricas são utilizadas para a seleção dos parâmetros do processo de extrusão. A caracterização mecânica e metalúrgica do material de trabalho é realizada e utilizada como dados de entrada para as abordagens de análise do processo. Considerando a força de conformação e as solicitações sobre as ferramentas, foram definidos o ângulo de extrusão e o dimensionamento do encarcaçamento da matriz. Os resultados analíticos e numéricos são comparados a dados experimentais. A precisão das análises foi comprovada pela concordância de 3% entre cálculos analíticos e simulações numéricas. Essa abordagem demonstra a eficácia da combinação de métodos para otimização de processos, visando sustentabilidade e competitividade para a indústria parafuseira.

Objetivo: O trabalho tem como objetivo otimizar o processo de fabricação de parafusos telheiros com cabeça sextavada flangeada, propondo uma nova rota de fabricação que inclui uma operação de extrusão direta, resultando em uma redução de 7% no consumo de matéria-prima.

Referencial Teórico: O estudo baseia-se em abordagens analíticas e numéricas aplicadas à seleção de parâmetros de processos de conformação a frio, considerando a caracterização mecânica e metalúrgica de materiais. Esse embasamento permite integrar métodos de análise e experimentação visando ganhos de eficiência, sustentabilidade e redução de custos no setor industrial.

Método: A pesquisa utilizou arames de aço baixo carbono SAE 1004 para a fabricação dos fixadores em duas etapas de conformação a frio. A nova rota incluiu a adição de uma etapa de extrusão direta. A caracterização mecânica e metalúrgica do material foi realizada para fornecer dados de entrada às análises. Parâmetros como força de conformação, solicitações sobre as ferramentas, ângulo de extrusão e dimensionamento do encarcaçamento da matriz foram definidos com base em análises analíticas e numéricas.

Resultados e Discussão: Os resultados obtidos demonstraram a eficácia da proposta. A força de conformação e o comportamento das ferramentas foram adequados à nova rota de fabricação. Comparações entre os cálculos analíticos, simulações numéricas e experimentos apresentaram uma concordância de 3%, comprovando a precisão das análises e validando o modelo proposto. Essa abordagem evidencia a viabilidade de combinar métodos analíticos e experimentais para otimizar processos industriais.

Implicações da Pesquisa: A pesquisa contribui para a indústria parafuseira ao demonstrar que a otimização de processos com base em métodos integrados pode melhorar a sustentabilidade e a competitividade. A redução no consumo de matéria-prima e a aplicação de ferramentas analíticas e numéricas representam avanços importantes para a eficiência e a inovação em processos de fabricação.

Originalidade/Valor: O estudo apresenta uma abordagem inovadora ao integrar métodos analíticos, numéricos e experimentais para otimizar processos industriais de conformação a frio, especificamente na fabricação de parafusos. A originalidade reside na inclusão de uma operação de extrusão direta à rota de fabricação convencional, resultando em uma redução de 7% no consumo de matéria-prima, um avanço significativo para a sustentabilidade e a eficiência industrial. Além disso, a precisão comprovada entre os diferentes métodos de análise agrega valor ao fornecer uma solução robusta e aplicável à indústria parafuseira, contribuindo para práticas mais sustentáveis e competitivas.

Palavras-chave: Análise Analítica, Extrusão Direta, Análise de Elementos Finitos, Forjamento.

OPTIMIZACIÓN DEL PROCESO DE EXTRUSIÓN EN FRÍO DEL ACERO SAE 1004 PARA LA PRODUCCIÓN DE TORNILLOS HEXAGONALES CON CABEZA FLANGEADA

RESUMEN

Introducción: Este estudio tiene como objetivo optimizar el proceso de fabricación de tornillos hexagonales con cabeza flangeada para techos. El fijador se produce en dos etapas de conformado en frío utilizando alambres de acero de bajo carbono SAE 1004. Se propone la adición de una operación de extrusión directa a la ruta de fabricación, lo que resulta en una reducción del 7% en el consumo de materia prima. Se emplean enfoques analíticos y numéricos para seleccionar los parámetros del proceso de extrusión. La caracterización mecánica y metalúrgica del material de trabajo se realiza y se utiliza como datos de entrada para los enfoques de análisis del proceso. Considerando la fuerza de conformado y las tensiones en las herramientas, se definieron el ángulo de extrusión y las dimensiones del recubrimiento de la matriz. Los resultados analíticos y numéricos se comparan con datos experimentales. La precisión de los análisis fue validada con una concordancia del 3% entre los cálculos analíticos y las simulaciones numéricas. Este enfoque demuestra la efectividad de combinar métodos para la optimización de procesos, apuntando a la sostenibilidad y competitividad en la industria de fijadores.

Objetivo: El estudio tiene como objetivo optimizar el proceso de fabricación de tornillos hexagonales con cabeza flangeada para techos, proponiendo una nueva ruta de fabricación que incluye una operación de extrusión directa, lo que resulta en una reducción del 7% en el consumo de materia prima.

Marco Teórico: El estudio se basa en enfoques analíticos y numéricos aplicados a la selección de parámetros para procesos de conformado en frío, considerando la caracterización mecánica y metalúrgica de los materiales. Esta base permite integrar métodos de análisis y experimentación, apuntando a mejoras en eficiencia, sostenibilidad y reducción de costos en el sector industrial.

Método: La investigación utilizó alambres de acero de bajo carbono SAE 1004 para la fabricación de fijadores en dos etapas de conformado en frío. La nueva ruta incluyó la adición de una etapa de extrusión directa. Se realizó la caracterización mecánica y metalúrgica del material para proporcionar datos de entrada a los análisis. Parámetros como la fuerza de conformado, las tensiones en las herramientas, el ángulo de extrusión y las dimensiones del recubrimiento de la matriz se definieron con base en análisis analíticos y numéricos.

Resultados y Discusión: Los resultados obtenidos demostraron la eficacia de la propuesta. La fuerza de conformado y el comportamiento de las herramientas fueron adecuados para la nueva ruta de fabricación. Las comparaciones entre los cálculos analíticos, las simulaciones numéricas y los experimentos mostraron una concordancia del 3%, lo que demuestra la precisión de los análisis y valida el modelo propuesto. Este enfoque resalta la viabilidad de combinar métodos analíticos y experimentales para optimizar procesos industriales.

Implicaciones de la Investigación: La investigación contribuye a la industria de fijadores al demostrar que la optimización de procesos basada en métodos integrados puede mejorar la sostenibilidad y la competitividad. La reducción en el consumo de materia prima y la aplicación de herramientas analíticas y numéricas representan avances significativos en eficiencia e innovación en procesos de fabricación.

Originalidad/Valor: El estudio presenta un enfoque innovador al integrar métodos analíticos, numéricos y experimentales para optimizar procesos industriales de conformado en frío, específicamente en la fabricación de tornillos. La originalidad radica en la inclusión de una operación de extrusión directa en la ruta de fabricación convencional, lo que resulta en una reducción del 7% en el consumo de materia prima, un avance significativo para la sostenibilidad y la eficiencia industrial. Además, la precisión demostrada entre los diferentes métodos de análisis agrega valor al proporcionar una solución robusta y aplicable para la industria de fijadores, contribuyendo a prácticas más sostenibles y competitivas.

Palabras clave: Análisis Analítico, Extrusión Directa, Análisis de Elementos Finitos, Forja.

1 INTRODUCTION

The global screw market was estimated at US$ 43.76 billion in 2022 and is expected to grow to approximately US$ 68.62 billion by 2032 (PRECEDENCE RESEARCH, 2023). The manufacturing processes adopted by fastener producers follow similar technologies and methods, which results in low differentiation between products. Furthermore, screws are widely marketed as standardized items, with limitations on customization, which intensifies competition in the sector. Thus, price becomes one of the determining factors for customers' choice of suppliers.

In this scenario, an effective strategy to reduce production costs and increase competitiveness consists of investing in improvements in engineering and optimization of production processes. Such initiatives allow for increased productivity, minimized waste and promoted more efficient use of energy and raw materials.

In order to develop a high-quality product, a thorough understanding of the manufacturing process is essential. This ensures that the advantages of the process are fully exploited and that the desired technical characteristics are achieved (VOLLRATH, 2013). In the case of forged products, it is crucial to precisely define the processing conditions during the design phase, thus avoiding additional costs after production has begun. A detailed understanding of the manufacturing stages, forging forces, and stress and strain distribution is essential for successful tool production. Therefore, it is necessary to adopt efficient methods that allow for the design of tools in an agile and optimized manner.

Technological advances in computing over the last few decades have enabled the use of numerical simulations to significantly improve the design of mechanical forming processes. Several commercial software programs based on the Finite Element Method (FEM) have been developed to analyze and solve classic challenges in the design of new forged parts. As a result, the experience of designers has been supplemented by numerical analysis, reducing the need for time-consuming and costly tests and experiments.

Another well-established approach is the use of analytical calculations. This methodology is particularly useful for quick estimates and simplified analyses, and is widely used to predict forging forces and stresses with a level of accuracy satisfactory for engineering. In addition, the calculations help designers understand the impacts of different parameters of the forging process (ALTAN, 2005).

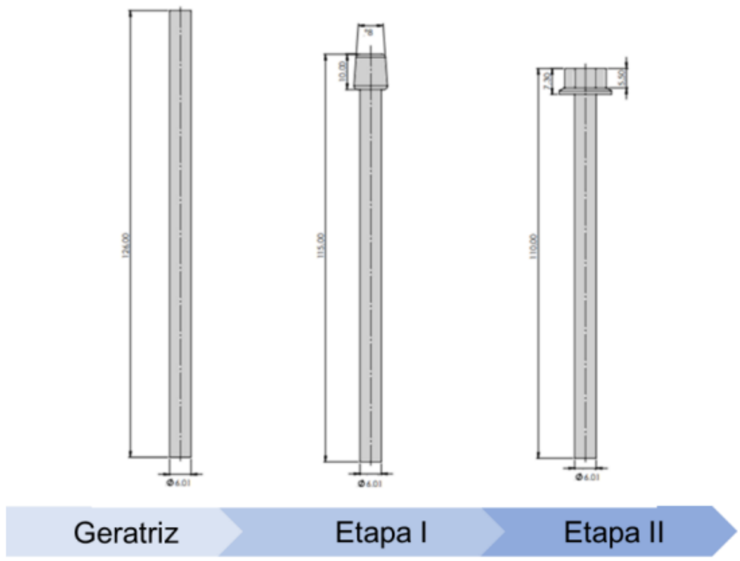
In this work, these approaches are applied to the cold forging design of a flanged hexagonal head bolt. The analyses aim to optimize the extrusion angle during the intermediate operation to obtain the preform.

2 DEFINITION OF THE PROPOSED METHOD

The objective of this study is to improve the manufacturing process of roofing screws. Currently, this fastener is produced in two forging stages, as illustrated in Figure 1. In the first stage, the preform required for the second phase, which corresponds to the finishing, is formed. After this stage, the geometry obtained is subjected to a rolling process, where the thread is formed, resulting in a screw with a flanged hexagonal head.

Figure 1

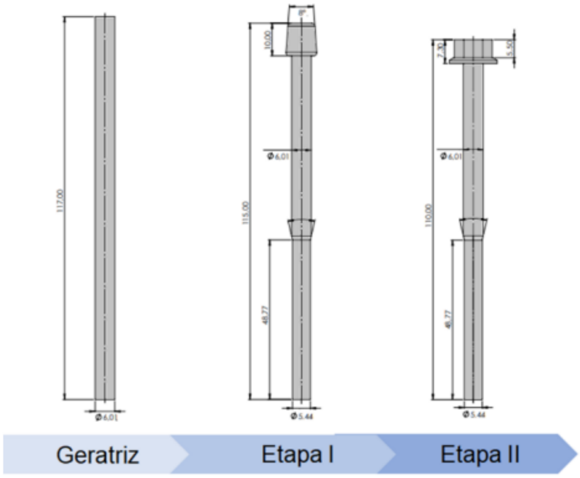
Roofing screw forging steps.



To increase efficiency in the use of raw materials and reduce production costs, a new manufacturing route was proposed (Figure 2). The initial stage, previously limited to simple pressing, now includes direct extrusion of the screw body. This additional material flow facilitates adequate filling during the final forming stage of the hexagonal head, also allowing the initial dimension of the generator to be reduced.

Figure 2

New method proposed for roofing screw optimization.



The development of this new forming stage requires a precise choice of the extrusion angle. This seeks to improve the efficiency of the process, reducing the force required for forging, energy consumption and wear on the tools used.

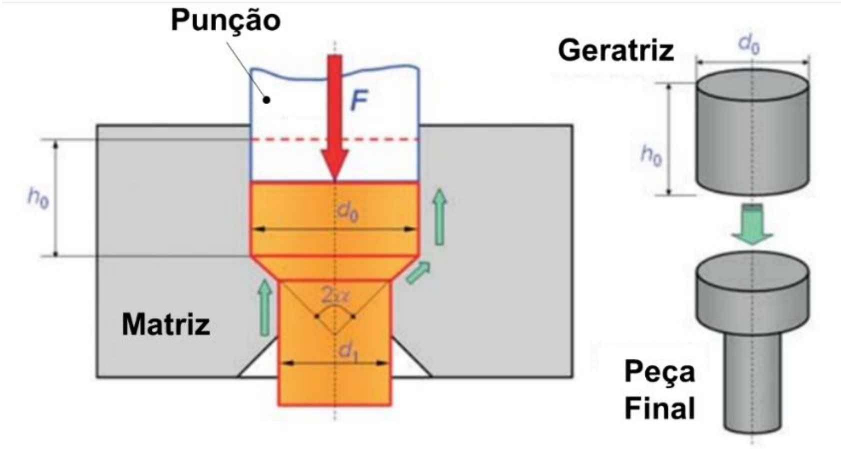
3 THEORETICAL FRAMEWORK

3.1 DIRECT EXTRUSION PROCESS

Extrusion processes can be classified based on the direction of material flow in relation to the movement of the tool or according to the geometry of the formed part, whether solid or hollow (LANGE, 1985). In the solid direct extrusion process investigated in this work, the material flows in the same direction as the movement of the machine punch, and the final product is a solid part with a profile defined by the shape of the die, as shown in Figure 3.

Figure 3

Schematic of the direct extrusion process. [JURKOVIC,2009]



To define maximum force in the direct extrusion process, the MONTGOMERY (2003) equation is used, defined as follows:

$$F = A_0 \cdot k_{fm} \cdot \varphi \cdot \left(1 + \frac{2\mu}{\sin 2\propto} + \frac{2}{3} \cdot \frac{\propto}{\varphi}\right) + \pi \cdot d_0 \cdot \mu \cdot k_{f0} \cdot h_k \quad (1)$$

Where d_0 is the diameter of the generatrix, k_{fm} is the mean yield stress, h_k is the unextruded height, A_0 is the initial area of the generatrix, μ is the coefficient of friction, α is the die angle and φ is the true strain in relation to the area.

The true strain (φ) in the direct extrusion process is calculated by equation 2:

$$\varphi = ln\frac{A_0}{A_1} \quad (2)$$

Where A_0 and A_1 are, respectively, the areas of the generator before and after the forming process.

4 MATERIALS AND METHODS

The main objective of this study is to optimize the angle of the extrusion die used in the forming of a preform of a roofing screw with a flanged hexagonal head. The focus of the analyses is exclusively on this stage of the process, with the evaluation of three different angles:

11°, 13° and 15°. For this purpose, both analytical calculations and numerical simulations were used, limited to the direct extrusion operation.

SAE 1004 steel was the material chosen for the manufacture of the screws. The chemical characterization of this steel was performed by means of spark optical emission spectrometry, the results of which are presented in Table 1. The chemical composition obtained is in accordance with the nominal ranges reported in the literature (NAYAR, 2021).

Table 1

Chemical composition of SAE 1004 steel (%).

Material	W	Mn	P	S
SAE 1004	0.03	0.26	0.013	0.011
SteelVisa	0.04	0.25 – 0.40	0.03	0.03

The force required for extrusion is directly related to the mechanical properties of the material in question. Therefore, in order to make reliable predictions, whether by numerical or analytical methods, it is essential to know the material's flow curve. Data on mechanical behavior were obtained through uniaxial tensile tests. These tests were conducted on an EMIC brand universal testing machine, with a maximum capacity of 600 kN, following the guidelines established by ASTM E8/E8M-21 (ROSIAK, 2020). The test samples had a useful length of 50 mm and were machined from SAE 1004 steel wire rods with a diameter of 6 mm.

Numerical simulations were performed using QFORM software, employing the finite element method to model the extrusion process. Considering the axial symmetry of the geometries involved, it was decided to perform the simulations in 2D. This approach simplifies the model, reducing the number of elements generated and the computational effort. In addition, this simplification allows for a more detailed refinement of the mesh, which contributes to obtaining more accurate and reliable results.

Table 2 presents the main mechanical and operational parameters used in the computational simulation and in the definition of the analytical calculations.

Table 2

Thermal, mechanical and operational parameters used in the numerical simulation of the extrusion process.

Generatrix material	SAE 1004
Generatrix temperature	20°C
Generatrix mesh type	Triangular
Matrix material	Carbide G-40
Punch material	AISI H13
Extractor material	AISI H13
Tool temperature	20°C
Coefficient of friction	0.05
Forming machine	Eccentric press
Relationship between crank radius and connecting rod length	0.17
Stroke length	200mm

Due to the elastoplastic material behavior, the forming generator was assigned, considering the Von Mises Yield Criterion. To simplify the calculations, the tools were treated as rigid bodies. The friction coefficient at the contact interfaces was defined as constant, with a value of 0.05. The forming machine used in the process is an eccentric press, whose kinematic data were incorporated into the numerical model for a more accurate analysis.

5 RESULTS AND DISCUSSIONS

5.1 FLOW CURVE

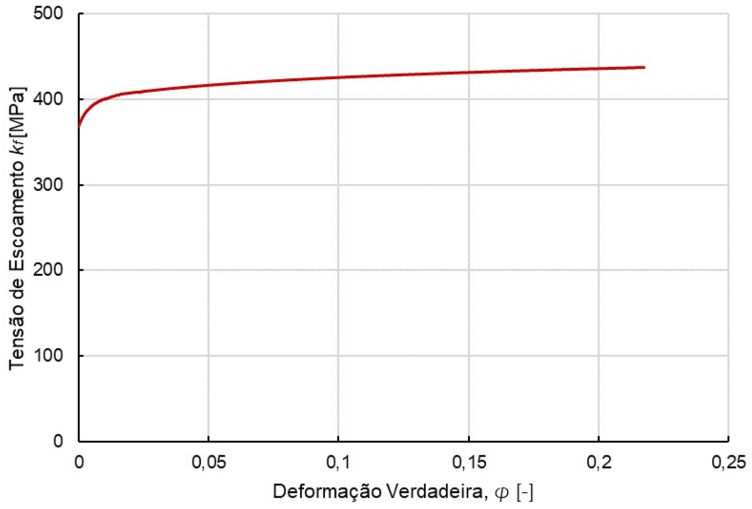
The yield curve of SAE 1004, obtained experimentally at room temperature, is shown in Figure 4. Under these conditions, the yield strength of the material was determined to be 360 MPa. From the results obtained, plotted on logarithmic scales, the work hardening coefficient (n) and the strength coefficient (C) were calculated, which characterize the behavior of the material during cold deformation. The Hollomon equation, which represents this relationship, can be expressed as:

$$k_f = 602.\varphi^{0,12} \qquad (3)$$

In this case, the strength coefficient is 602 MPa, while the work hardening coefficient is 0.12. Based on equation 3, it is possible to estimate the force required for the cold forging process, evaluate the mechanical properties of the formed parts and perform a detailed characterization of the material behavior through numerical analyses based on the finite element method [10].

Figure 4

SAE 1004 flow curve.



Due to its low carbon content, SAE 1004 steel has a reduced mechanical strength. This is advantageous in terms of deformability, since materials with higher strength tend to reach the critical stresses that lead to fracture more quickly. In addition, the yield stress plays a crucial role in influencing the stresses transmitted to the forming tools, which can impose limitations on the geometric complexity of the part. More complex geometries generally result in stress increases that can exceed the strength limits of the tool material [10].

Table 3

Mechanical properties of SAE 1004 obtained in uniaxial traction.

Material	$R_{p0,2}$ $[MPa]$	R_m $[MPa]$	A [%]
SAE 1004	360	390	22

The mechanical properties obtained through tensile tests are listed in Table 3. The yield strength and tensile strength values found are within the ranges specified in the literature. However, the observed elongation was below that expected for this material, indicating a slightly different behavior in relation to the usual standard.

5.2 EXTRUSION PROCESS

In the analyzed extrusion process, the initial diameter of the generator was set at 6 mm, while the final section obtained after extrusion has a diameter of 5.44 mm. Three different tool configurations were evaluated, each with die angles of 11°, 13° and 15°, seeking to identify the conditions that would optimize deformation. The variation in the extrusion angle directly impacts the volume of the generator, influencing the process performance and the properties of the formed material. Table 4 presents the volumes of the generator corresponding to each angle configuration investigated.

Table 4

Effect of extrusion angle on the volume of material used in the process.

Extrusion Angle, α [°]	Volume of material, V [mm^3]
11	3305.82
13	3306.42
15	3306.86

When comparing the current screw manufacturing method (as illustrated in Figure 1) with the new proposed approach, which incorporates the extrusion step, a reduction of approximately 7% in raw material consumption was observed. This saving reflects not only a reduction in production costs, but also an advance in terms of efficiency in the use of resources, enabling greater sustainability and competitiveness in the production process.

5.3 ANALYTICAL CALCULATIONS

Table 5 presents the maximum force values obtained by the analytical method, using equation 1 for the three conditions analyzed.

Table 5

Effect of extrusion angle on extrusion force.

Extrusion Angle, α [°]	Extrusion Force, F $[kN]$	Extrusion Force, F $[t]$
11	23.26	2.37
13	23.75	2.42
15	24.21	2.47

The force required for direct extrusion is mainly influenced by the mechanical properties of the material, the logarithmic deformation (φ), the die angle (α), the coefficient of friction

(μ) and the initial geometry of the generatrix (JURKOVIC, 2009). In the analyses performed, only the die angle and the unextruded height (h_k) were adjusted. The height h_k was changed in order to keep the length of the rod and screw thread constant, even with the variation of the extrusion angle. As the other parameters of equation 1 remained unchanged, the calculated extrusion force presented minimal variations between the different scenarios.

5.4 NUMERICAL SIMULATION

The material flow and stress distribution during the extrusion process are strongly dependent on the die design (KONG, 2002). To understand the influence of the die angle on the kinematic characteristics of the process, detailed numerical simulations were performed.

Figure 5 illustrates the distribution of equivalent deformation after extrusion for the different angles evaluated. The variation of the extrusion angle directly impacts the material flow, changing the way in which the plastic deformation is distributed. It was observed that the maximum value of φ_{eq} increased from 0.36 (for α = 11°) to 0.54 (for α = 15°), highlighting the significant influence of the die angle on the material behavior.

Figure 5

Equivalent strain distribution along the extruded part.

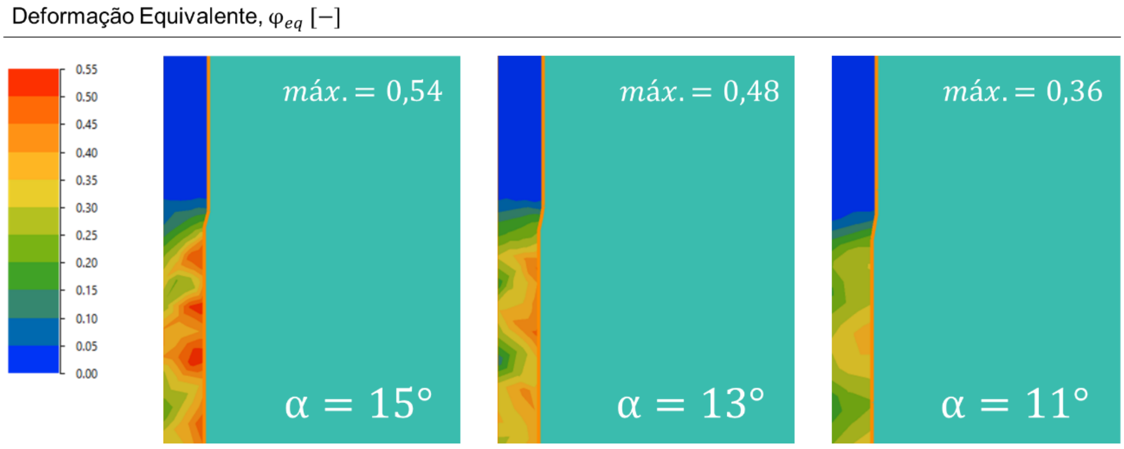


Figure 6

Equivalent stress distribution along the extruded part.

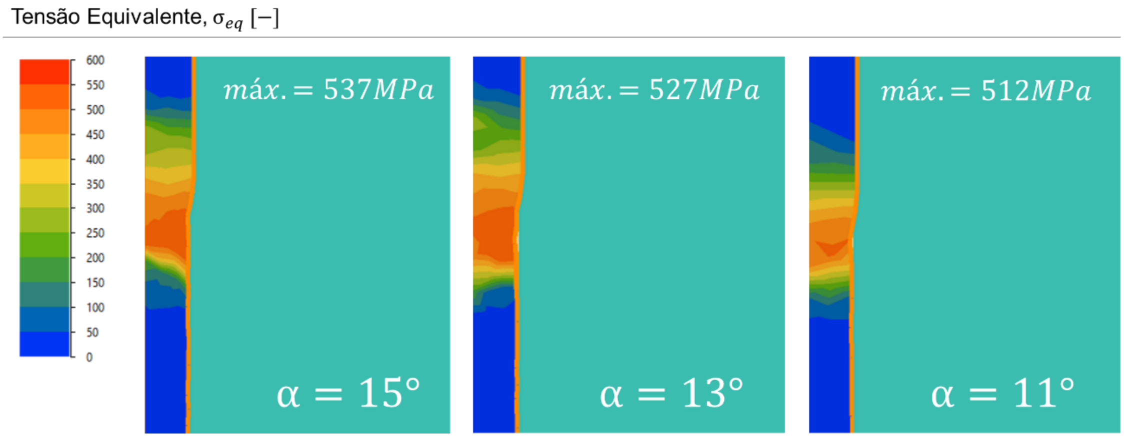
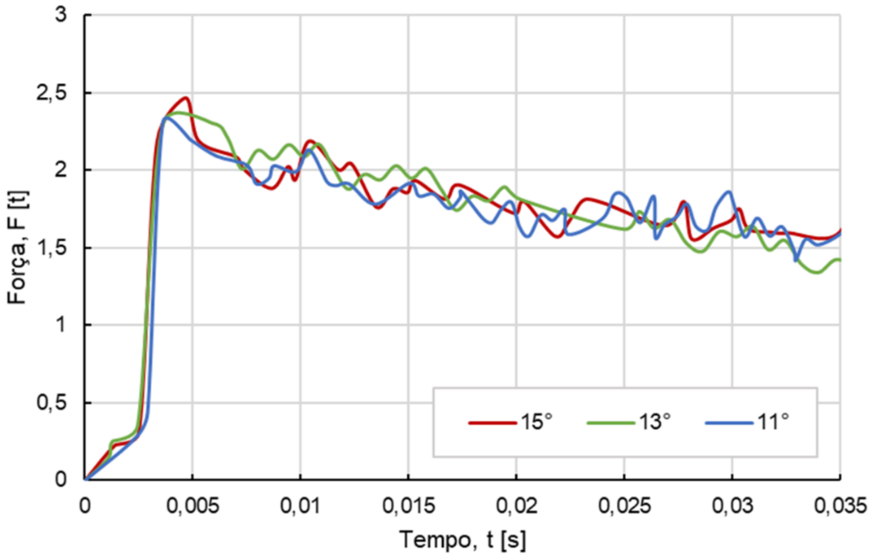


Figure 6 shows the equivalent stress distribution obtained numerically after the extrusion process. It was observed that, with the increase in the die angle, the equivalent stress in the work material also increases, indicating a direct relationship between the extrusion angle and the mechanical effort required by the process. Figure 7 demonstrates the variation of forces in the extrusion process, for the variations in the die entry angles.

Figure 7

Variation of forming force with time.



The numerical results obtained by finite elements demonstrated consistency with the analytical predictions, confirming that the forming force increases with the die angle. For the evaluated angles, the maximum simulated forces were 2.30 t for α = 11°, 2.35 t for α = 13° and

2.49 t for α = 15°. The maximum deviation between the analytical and numerical approaches was only 3%, evidencing the accuracy of the applied methodologies.

6 CONCLUSIONS

In this study, analytical and numerical analyses were combined to optimize the manufacturing process of a flanged hexagonal head roofing screw, focusing on the direct extrusion step. The proposed manufacturing route allowed a 7% reduction in raw material consumption compared to the traditional method, bringing significant economic benefits and promoting more sustainable practices.

The results highlight the importance of an adequate design of the extrusion tools, since the die angle directly influences the distribution of stress and deformation during the process. In addition, the analyses performed demonstrated the efficiency and reliability of the methodologies employed, contributing to a greater understanding of the material behavior.

The research reinforces the relevance of integrating engineering knowledge, analytical methods and numerical simulation technologies in improving industrial processes. This integrated approach not only improves production efficiency, but also ensures the quality of the final product and strengthens market competitiveness.

Finally, the results obtained show that the application of advanced analysis tools is essential for innovation in industrial processes. The model adopted in this study can serve as a reference for optimizing processes in various sectors, promoting efficiency, sustainability and operational excellence.

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