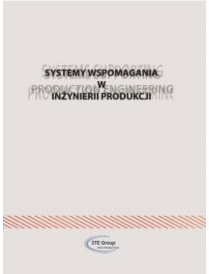
Cold Forming of Steel – Selected Processes, Issues, and CAx

Data wpłynięcia do Redakcji: 11/2024
Data akceptacji przez Redakcję do publikacji: 11/2024

2024, volume 13, issue 1, pp. 41-54



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Abstract: This paper presents an analysis of the key challenges and irregularities associated with metal plastic deformation processes, with particular emphasis on phenomena such as springback, wrinkling, folding, cracking, microcracking, and burr formation. These undesirable effects can negatively impact the quality of final products and their mechanical properties, as well as the durability of tools used in processes such as bending, stamping, spinning, and cutting. The paper discusses the mechanisms leading to the formation of these defects, highlighting the role of process conditions, such as stress, processing speed, and tool geometry, which can cause technological issues. It also emphasizes the significance of tool wear, particularly in cutting processes, where abrasive, adhesive, and fatigue wear can lead to burr formation and deterioration in the quality of cut components. The study further explores methods to minimize these defects through process parameter optimization and proper tool design. Special attention is given to the use of numerical tools, such as the finite element method (FEM), which enables precise modeling of stress and strain distributions and the prediction of potential defect locations. Advanced simulations allow for improved prediction of issues like cracking, wrinkling, and springback, which ultimately enhances the quality of deformation processes and final products. The paper also highlights the need for further research in plastic deformation and the development of numerical models, particularly in the context of accounting for microstructural changes and residual stresses in materials.

Keywords: plastic forming, numerical analysis, FEM, spinning, bending, cutting, drawing

INTRODUCTION

Cold working is a commonly used process in manufacturing plants within the automotive, railway, aerospace, construction, and even food industries. In other words, it is applied wherever steel is utilized for production. A significant benefit of this process is the substantial increase in strength properties, such as in stainless steel (Coetsee et al., 1990; Afshan et al., 2013). Numerous scientific studies have demonstrated that effective structural design requires the use of such processes to enhance structural strength (Ashraf et al., 2005; Rossi et al., 2013; Cruise and Gardner, 2008; Errera et al., 1974). The result of this process involves irreversible thermo-visco-plastic-phase deformations, which is why there are still many unexplored areas within this field of science.

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PURPOSE AND SCOPE OF THE STUDY

The purpose of this study is to analyze the key challenges in steel cold working processes, such as defects resulting from these processes. The elaboration discusses the impact of process conditions and tool geometry on defect occurrence, as well as the use of numerical methods, such as the Finite Element Method (FEM), for predicting and optimizing these processes.

CHALLENGES AND DEFECTS IN PLASTIC DEFORMATION PROCESSES

Plastic forming processes are one of the cornerstones of modern industry, enabling precise steel shaping and often resulting in complex forms. However, their extensive application continues to bring numerous challenges and potential defects that can affect the quality, strength, or durability of the final product (Yang et al., 2018). Notable phenomena include springback, wrinkling, folding, cracking, microcracks, and the formation of burrs. It is also important to mention not only the final product but also the wear and tear of the tools and equipment involved in the process (Sugita and Arai, 2015; Russo et al., 2021; Watsom and Long, 2014). Each of these issues can adversely impact the final geometry and mechanical properties of the material.

Springback is a phenomenon that occurs after unloading, where the material partially returns to its original shape due to the non-uniform stress distribution within the material (Li et al., 2002). Based on current research, wrinkling (Fig. 1) arises when local compressive stresses in the material exceed its deformation capacity. This phenomenon is particularly evident in the spinning process, where bending forces and stresses generated by the tool create excessive local stress values at the sheet edges (Music et al., 2010; Russo et al., 2020; Xia et al., 2014).

Fig. 1 Metal spinning during the spinning process of an AISI 304 steel end cap

Source: Own study

An analogous phenomenon to wrinkling is folding, which in most cases accompanies stamping, where, for example, flange folding can result from an improperly designed blank holder. Figure 2 illustrates this defect, along with examples of shape defects in stampings.

Fig. 2 Defects in stampings – 1, 3, 4 – shape defects, 2 – folding

Source: Own study

The formation of burrs primarily concerns cutting processes, during which thin, sharp protrusions form on the edges of machined components. This can be caused by wear on the punch edge, such as frictional wear, adhesive wear, or fatigue (Bohdal et al., 2022).

The most serious defects in products subjected to plastic forming include cracking and surface microcracks, which may result from material defects, overloading, or excessive deformation. The location of the crack is associated with areas of highest local stresses and excessive thinning of the material (Kałduński, 2018).

Currently, one of the most significant challenges in the industry is the proficient use of CAx tools, with a focus on the FEM. This method allows for precise simulations of stress distributions, deformations, and material displacements, enabling the prediction of potential defect locations – such as cracks, wrinkling, and buc kling – or the mitigation of the springback phenomenon. This area of science, related to numerical modeling, also requires further development due to the high computational power needed and the advancement of models that account for changes in microstructure and residual stresses in the material (Bohdal et al., 2020; Bohdal et al., 2024; Bohdal et al., 2014; Patyk et al., 2022; Horajski et al., 2021).

SELECTED CHARACTERISTIC PHENOMENA ASSOCIATED WITH MATERIAL PLASTIC FORMING PROCESSES

Plastic forming is a technology that enhances material strength through hardening (isotropic, kinematic, or mixed) due to the retention of crystallographic structure (Imran and Walther, 2016). In the study by Walport F. et al., the impact of welding on material subjected to controlled deformation was investigated. Research on AISI 304 austenitic steel sheets showed that the welding process leads to complete softening of the material in the heat-affected zone, resulting in the loss of induced hardening within up to 50 mm from the weld (Walport et al., 2023). Depending on the material or deformation conditions, hardening curves may vary to some extent, yet the stress-strain curve generally retains a characteristic shape, as illustrated in Figure 3 (Imran and Walther, 2016; Wei et al., 2009).

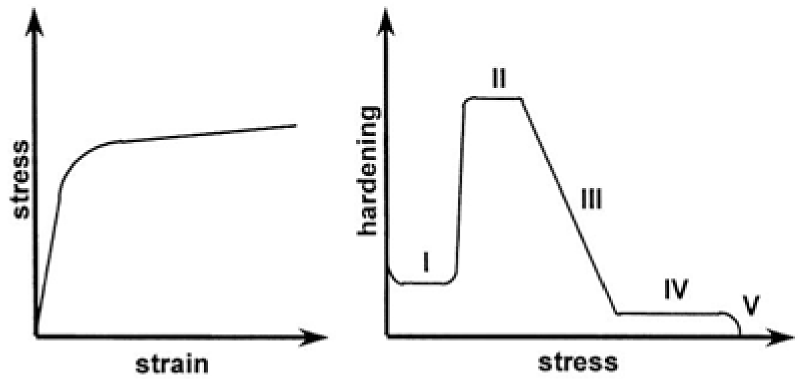

Fig. 3 Schematic stress–strain curve and hardening rate vs. stress for large strain plastic deformation of metals and alloys

Source: Imran and Walther, 2016

A study on the static tensile testing of AISI 316 stainless steel regarding the influence of temperature on its forming showed that lowering the material temperature to -50°C leads to a significant, uniform increase in elongation and a slight increase in hardness. However, this comes at the cost of reduced corrosion resistance compared to tensile testing at temperatures of 20°C, 300°C, and 700°C. Therefore, the application of technologies that lower the material temperature (e.g., using liquid nitrogen) before introducing plastic deformations is justified when increased strength is essential, with the understanding that there will be a deterioration in anti-corrosive properties (Bruschi et al., 2023).

REVIEW OF SELECTED COLD WORKING PROCESSES

Bending

The bending process is the most commonly used plastic forming process in manufacturing plants, ranging from the production of simple brackets and multi-stage bent cabinets and enclosures to products with more complex geometries. Bending (Fig. 4) is often employed for both functional and practical reasons, aiming to intentionally strengthen and stiffen the desired geometry. Despite its popularity, this process remains a topic of discussion and scientific research – aparticularly for materials that exhibit anisotropy (Miksza et al., 2022).

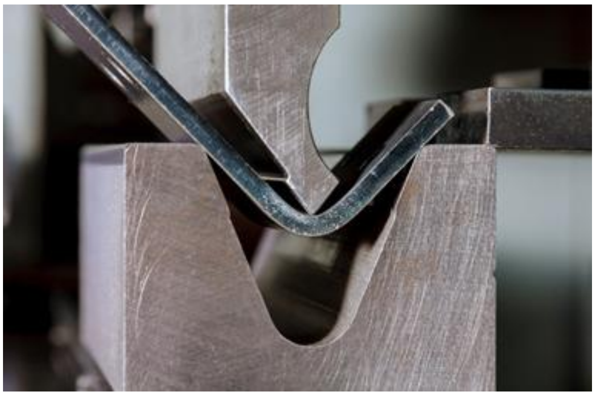

Fig. 4 Bending proces

Source: https://www.ogsindustries.com

One of the main challenges in plastic forming is the phenomenon of springback, which signifies an unexpected change in shape after unloading. This topic is frequently addressed, with modern engineering methods such as numerical analyses being utilized to mitigate it (Mulidrán et al., 2020; Lawanwong et al., 2020; Trzepieciński and Lemu, 2020).

In the study by Valentino T. et al., research was conducted on an innovative method for reducing springback by influencing the residual stress state in thin sheets before the bending process. It was shown that one of the causes of this undesirable phenomenon is non-uniform stresses resulting from previous machining processes. The applied method, based on preliminary laser treatment, confirmed an increase in the material's resistance to springback and achieved tighter tolerances without the need for costly solutions (Valentino et al., 2023).

Drawing

The industry related to plastic forming emphasizes the importance of creating mathematical and physical models, which enable a more accurate understanding of the physical phenomena occurring during stamping (Fig. 5). A common practice across all manufacturing processes is to intentionally assume that the stress state of the workpiece being processed is zero, whereas in reality, it is a component influenced by its production history (Yao and Cao, 2001; Trzepieciński and Gelgele, 2011).

One of the significant topics is the stamping of steel sheets using the FEM. In the study (Kałduński, 2018), this process was defined as a geometrically and physically nonlinear problem with unknown boundary conditions in the contact area between the tool and the material.

The author conducted an extensive analysis using advanced modeling that considered the stress and strain history from the preceding proces.

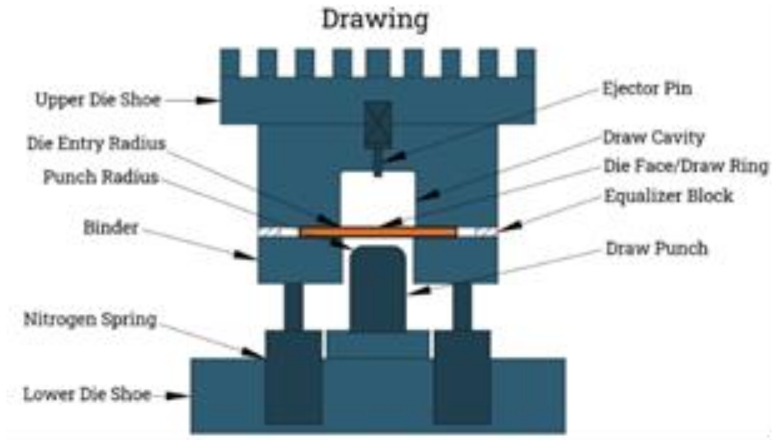

Fig. 5 Illustration of the drawing process

Source: https://www.iqsdirectory.com/articles/metal-stamping/die-stamping.htm

One of the main conclusions confirmed the validity of using FEM analyses to control the final product geometry, stamping force, and stress distribution. Figure 6 shows an example comparison of stress and geometry results of the stamped part before and after springback, also considering the stress history from previous processes.

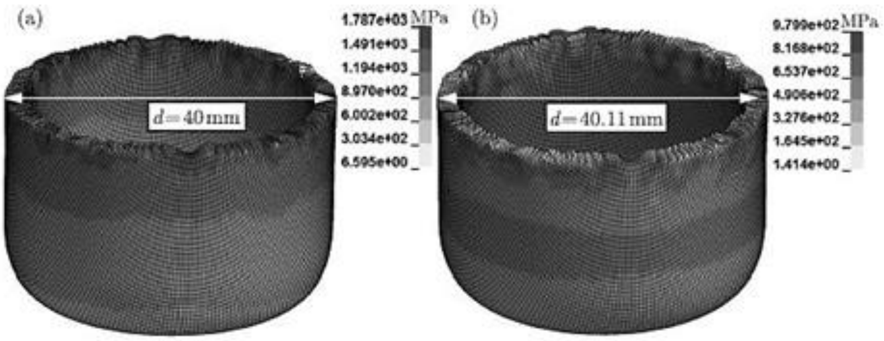

Fig. 6 Maps of the equivalent stress in the drawpiece with history: (a) before springback, (b) after springback

Source: Kałduński, 2018

In the study by Zhang P. et al. (Zhang et al., 2022), research was conducted on the stamping process of thin sheets, which enabled the creation of micro-channels in bipolar plates used in fuel cells. The research methodology aimed to analyze the formation of cracks and excessive material thinning caused by inaccuracies in the positioning of the stamping tool. Additionally, both simulation and experimental studies demonstrated that the hardness of the blank holder and its compression percentage were the parameters with the most significant impact on the folding of the final product.

Spinning

The spinning process is one of the less common plastic forming processes encountered in manufacturing enterprises. Sheet metal forming in the spinning process is also possible using a lathe. It requires specialized tooling and significant knowledge and experience from the operator. However, it does not guarantee consistent and repeatable product quality, which is also limited by the dimensions. In the era of growing demand and the expectation of high and repeatable quality, the use of automated CNC spinning machines becomes essential. Designing an optimal technological process that guarantees the intended functional quality of the product becomes key. The spinning process is shown in Figure 7.

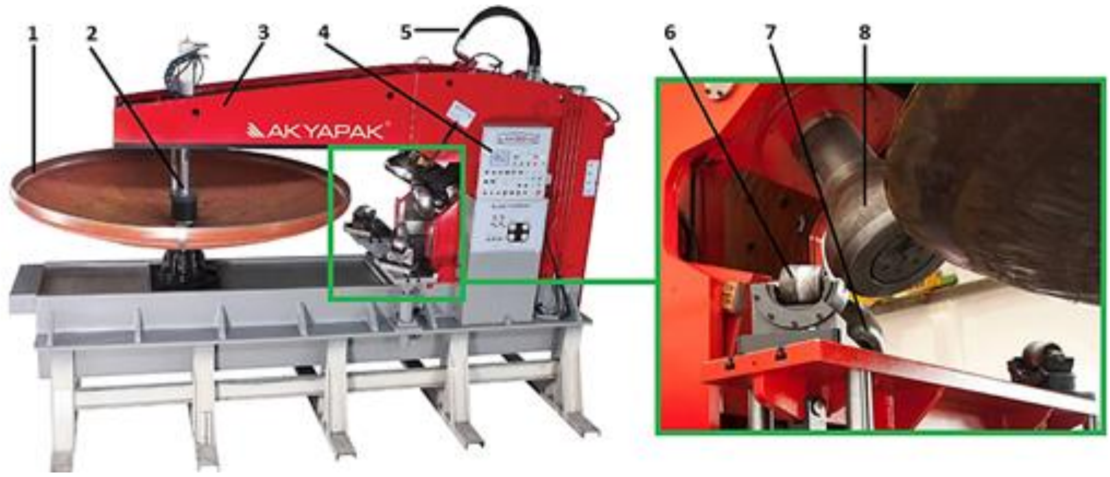

Fig. 7 The spinning process: 1 – workpiece, 2 – pressure pad, 3 – rigid frame, 4 – control panel, 5 – hydraulic power supply, 6 – support roller, 7 – pressure (forming) roller, 8 – shaping roller

Source: https://www.polteknik.pl

The geometric parameters and the quality of the finished product, as well as the stress states occurring within it, are determined by a number of factors related to both the material (stress state resulting from previous processing, thickness, surface condition, mechanical and chemical properties) and the technological process (forming roller speed, peripheral speed of the semi-finished product, pressure force of the shaping roller, number of passes in the forming process, roller radii, technical condition of forming tools, system rigidity).

The issues of this process focus on many aspects – from the predicted geometry of the object, elastic deformations, microstructure, post-processing stresses, damage prediction, to tool path design (Xia et al., 2014; Russo et al., 2021).

This type of processing largely relies on practical experience (Zhang et al., 2022). Simulation studies allow for the analysis of the technological process using appropriate models, and the results of these studies can be implemented in experimental applications (Keneshlou et al., 2023; Watsom and Long, 2014; Yu et al., 2020; Sebastiani et al., 2006; Kocabiçak and Abdel Wahab, 2022; Kleiner et al., 2002; Quigley and Monaghan, 2002), which is associated, among other things, with cost optimization.

The analyses contained in the study (Yu et al., 2020) showed that the phenomenon of material wrinkling is caused by residual stresses at the edge of the finished product. The work led by Jahazi M. (Jahazi and Ebrahimi, 2000)

presents an analysis of the impact of process parameters and microstructure state on product quality. The study identified optimal conditions for the process aimed at eliminating defects in the case of D6AC steel. Process parameters were analyzed by Sugita Y. (Sugita and Arai, 2015), where an asymmetrical product was examined.
The article (Watsom and Long, 2014) focused on the relationship between the shaping roller, the pressure roller, and the angle of its positioning in relation to the wrinkling and cracking of aluminum alloy. The results showed that the greatest material thinning (Russo et al., 2020) is located in the area of increased curvature.
The study by Yang D. and others (Yang et al., 2018) indicates that a desirable feature is the flexibility of the process, which can be facilitated by numerical analyses that contribute to reducing costly and time-consuming experimental research.

Cutting

Mechanical cutting finds wide application despite the ongoing development of laser processing technology. On the one hand, this is due to the high efficiency of the process, and on the other, specific requirements, such as for shaping magnetic materials, which are particularly sensitive to thermal deformations after cutting (Bohdal et al., 2024; Bohdal et al., 2022). Cutting operations, such as punching, piercing, shearing, guillotine cutting, and cutting with disc shears, are key processes for production in the broadly understood machinery, automotive, electronics, and aerospace industries (Bohdal et al., 2019). Like the aforementioned plastic forming operations, cutting poses challenges related to maintaining the process, geometric precision, minimizing changes in physicochemical properties in the cutting area, tool buildup, tool wear, and the impact of this wear on the final product (Bohdal and Kukiełka, 2006; Hambli, 2001; Bohdal and Walczak, 2013; Abbas et al., 2017).
One of the punching techniques is contour cutting, which involves repeated punching and is widely used in plastic forming for both simple and complex shapes. It consists of gradually cutting the sheet with a series of holes to achieve the desired outline, as shown in Figure 8 (Bohdal et al., 2022).
The goal of the punching process is to increase efficiency and minimize the influence of heat compared to laser cutting, which affects the morphology of the material in the heat-affected zone. It is necessary to obtain a surface with a properly shaped cutting edge, free from burrs and without the accumulation of plastic deformations. The main factors influencing the final quality are the lubrication method, tool geometry, cutting speed, clearance between the punch and the die, the material properties of the punch, and its wear level (Abu Qudeiri et al., 2020; Arslan et al., 2016).

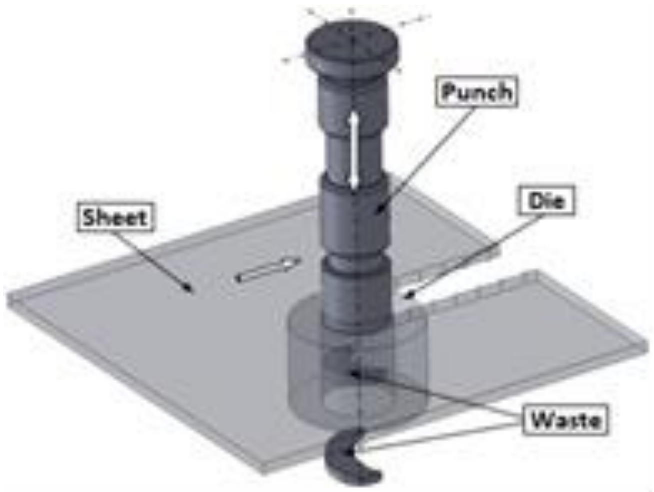

Fig. 8 Illustration of the nibbling proces

Source: Bohdal et al., 2022

Figure 9 shows a numerical analysis of the reduced stress state in the tool and perforated sheet for different stages of the punching process.

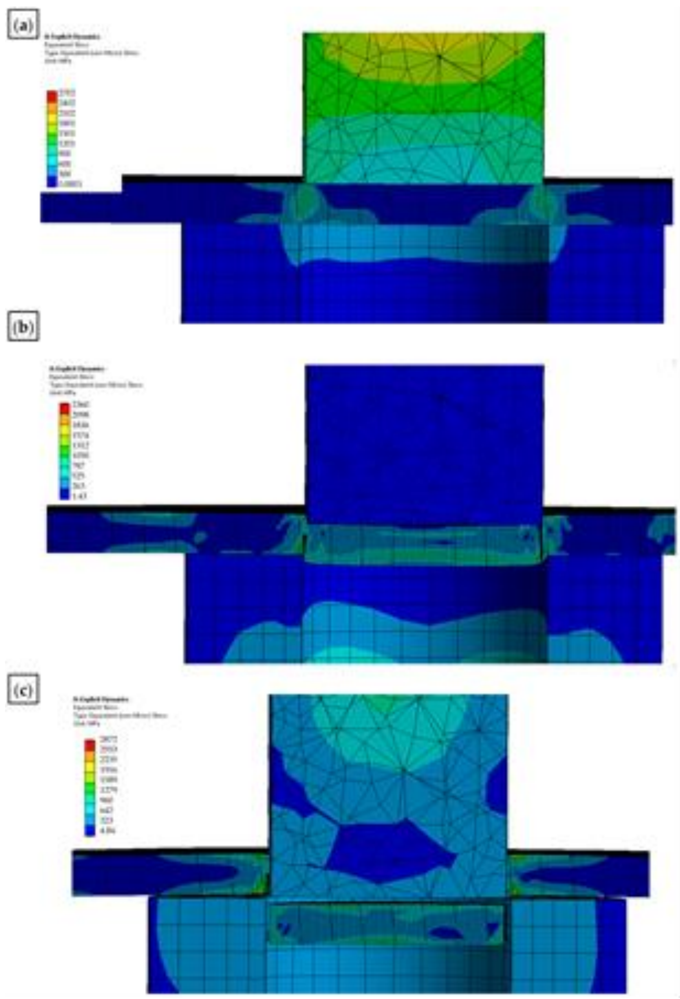

Fig. 9 The state of reduced stresses in the tool and the punched sheet for various levels of advancement of the process: (a) for 3% advancement; (b) for 10% advancement; (c) for 80% advancement [MPa]

Source: Bohdal et al., 2022

CONCLUSIONS

Cold plastic forming, although known for a long time and widely applied, still contains many unexplored areas. It can be confidently assumed that progress and discoveries in other fields drive the need for further research in this area.

Analyzing the above overview of current knowledge, it can be stated that present studies focus on refining technological processes and minimizing defects that negatively affect the quality and durability of products. The introduction of innovative methods, such as advanced numerical modeling using the finite element method, enables precise prediction of stress distributions, elastic springback phenomena, and potential defect areas in products, including cracks, wrinkling, or shape deviations. This enhances process control and improves final product quality without the necessity for costly experimental studies.

In the case of bending and stamping, the key challenge is the analysis of the elastic springback phenomenon and material cracking. Research in this field, such as the analysis of residual stresses or preliminary laser treatment, allows for a reduction in the impact of these phenomena, leading to optimal product geometries.

In the spinning process, research focuses on automation and the optimization of technological parameters to increase the repeatability and quality of manufactured components while avoiding wrinkling or excessive material thinning.

Studies on the state of the art in punching and cutting emphasize the need to enhance efficiency and minimize damage and burr formation on the edges. Various solutions are applied, including controlling the clearance between the punch and die, variable tool geometries, and appropriate tool lubrication methods.

From the perspective of technological advancement and the rapid pace of computer technology development, the FEM has become a key tool in the analysis of plastic forming processes and many other fields. It brings significant economic benefits by reducing the need for costly experiments and accelerating fatigue testing of materials. It allows for a precise understanding of phenomena in deformation processes and the analysis of stress distribution and concentration.

This tool enhances production stability, flexibility, and efficiency, supports sustainable development by minimizing energy and material consumption, reduces environmental impact, and increases the competitiveness of enterprises.

However, this method also has its limitations. The quality of simulation results can be affected by difficulties in ensuring consistent material properties and inaccuracies in material models that do not always accurately reflect the actual behavior of materials under different processing conditions. The development of this technology also requires substantial computational resources, which can be challenging for complex simulations. Despite these challenges, FEM remains an invaluable tool that, combined with tool optimization, significantly improves the efficiency and quality of production processes, giving companies a competitive edge.

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Obróbka plastyczna stali na zimno – wybrane procesy, problematyka, CAx

Streszczenie: Niniejsza praca przedstawia analizę kluczowych wyzwań i nieprawidłowości związanych z procesami deformacji plastycznej metali, ze szczególnym uwzględnieniem takich zjawisk jak powrót sprężysty, marszczenie, fałdowanie, pękanie, mikropęknięcia oraz powstawanie gratu. Te niepożądane efekty mogą negatywnie wpływać na jakość finalnych produktów oraz ich właściwości mechaniczne, a także na trwałość narzędzi wykorzystywanych w procesach, takich jak gięcie, tłoczenie, wyoblanie czy cięcie. W pracy omówiono mechanizmy prowadzące do powstawania tych wad, zwracając uwagę na rolę warunków realizacji procesu i zjawisk fizycznych, takich jak naprężenia, prędkość obróbki oraz geometrię narzędzi, które mogą prowadzić do problemów technologicznych. Podkreślono również znaczenie zużycia narzędzi, w szczególności w kontekście procesów cięcia, gdzie zużycie cierne, adhezyjne oraz zmęczeniowe może prowadzić do powstawania gratu oraz pogorszenia jakości ciętych elementów. Analizowano także metody minimalizowania wspomnianych wad poprzez optymalizację parametrów procesowych i odpowiednie projektowanie narzędzi. Szczególną uwagę poświęcono wykorzystaniu narzędzi numerycznych, takich jak metoda elementów skończonych (MES), która pozwala na precyzyjne modelowanie rozkładów naprężeń, odkształceń oraz przewidywanie miejsc potencjalnych wad. Dzięki zaawansowanym symulacjom możliwe jest lepsze przewidywanie zjawisk takich jak pękanie, fałdowanie czy powrót sprężysty, co pozwala na poprawę jakości procesów deformacyjnych i produktów końcowych. Wskazano również na potrzebę dalszych badań w zakresie obróbki plastycznej oraz rozwoju modeli numerycznych, szczególnie w kontekście uwzględniania zmian mikrostrukturalnych i naprężeń resztkowych w materiałach.

Słowa kluczowe: obróbka plastyczna, analiza numeryczna, MES, wyoblanie, gięcie, cięcie, tłoczenie

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