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Evaluation of surface and dimensional phenomena in punching of DP800 advanced strength steel utilising the Cockcroft-Latham Damage Model

Cockcroft-Latham hasar modeli kullanılarak DP800 ileri mukavemetli çelik delme-zımbalama işleminde yüzey ve boyut olayların değerlendirilmesi

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Evaluation of Surface and Dimensional Phenomena in Punching of DP800 Advanced Strength Steel Utilising The Cockcroft-Latham Damage Model

Highlights

- *The punching behaviour of DP800 steel was analysed experimentally and numerically*
- *The critical damage constant C = 1.5 was validated using the CL model.*
- *The shear zone accounted for ~28% of the sheet thickness.*
- *The P16 punch yielded the most accurate 20 mm hole diameter.*
- *The P16 punch produced the lowest burr and best surface quality.*

Graphical Abstract

Cutting-surface characteristics and damage evolution of DP800 steel were analysed under different punch geometries.

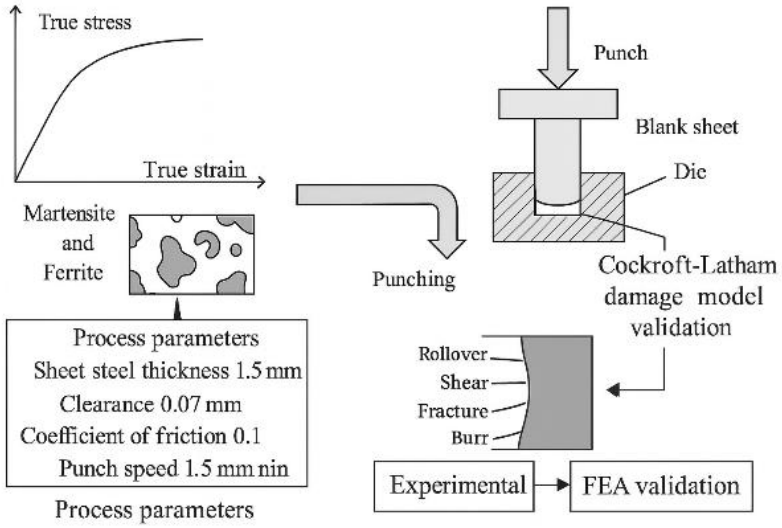


Figure. Graphical abstract of the article

Aim

The aim is to determine the effect of punch geometry on surface quality and damage in DP800 steel.

Design & Methodology

Experiments with five punch geometries and 2D FE analyses using the CL model were conducted.

Originality

One of the few studies examining punch-geometry effects on shear zone, burr and damage behaviour of DP800 steel.

Findings

The P16 punch produced the lowest force, smallest burr and the most accurate hole diameter.

Conclusion

The study supports defining optimal punch geometry for DP800 and provides criteria to improve manufacturing precision.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Evaluation of Surface and Dimensional Phenomena in Punching of DP800 Advanced Strength Steel Utilising The Cockcroft-Latham Damage Model

Araştırma Makalesi / Research Article

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ABSTRACT

This study presents a quantitative and original investigation of the punching behaviour of DP800 advanced high-strength steel (AHSS), widely used in automotive components due to its high strength-to-weight ratio. Experimental tests on 1.5 mm thick DP800 sheets revealed a maximum true stress of ~900 MPa, accompanied by uniform elongation behaviour. Five distinct punch geometries were evaluated, among which the P16 punch produced the smoothest cutting surface and the lowest burr height (0.08 mm), while the flat punch yielded 0.11 mm. Finite element simulations performed using the Cockcroft–Latham (C–L) damage model confirmed a critical damage constant of C = 1.5, which agrees with the experimental results. The shear zone accounted for approximately 28% of the total sheet thickness, and dimensional accuracy measurements indicated that the P16 punch achieved hole diameters closest to the nominal 20 mm. Unlike previous studies that primarily focused on the general behaviour of AHSS, this work provides a detailed quantitative analysis of DP800 punching mechanics and surface quality. The findings deliver novel insights into tool-geometry optimisation and damage prediction, offering practical guidelines for improving manufacturing precision and process reliability in AHSS forming operations.

Keywords: Dual-phase steels, punching, shear surface, FEA.

Cockcroft-Latham Hasar Modeli Kullanılarak DP800 İleri Mukavemetli Çelik Delme-Zımbalama İşleminde Yüzey ve Boyut Olayların Değerlendirilmesi

ÖZ

Bu çalışma, yüksek mukavemet-ağırlık oranı nedeniyle otomotiv bileşenlerinde yaygın olarak kullanılan DP800 gelişmiş yüksek dayanımlı çeliğin (AHSS) delme davranışının nicel ve orijinal bir araştırmasını sunmaktadır. 1,5 mm kalınlığındaki DP800 saclar üzerinde yapılan deneysel testler, düzgün uzama davranışıyla birlikte ~900 MPa'lık maksimum gerçek gerilmeyi ortaya koymuştur. Beş farklı delme geometrisi değerlendirilmiştir; bunlar arasında P16 delme en pürüzsüz kesme yüzeyini ve en düşük çapak yüksekliğini (0,08 mm) üretirken, düz delme 0,11 mm vermiştir. Cockcroft-Latham (C-L) hasar modeli kullanılarak gerçekleştirilen sonlu elemanlar simülasyonları, deneysel sonuçlarla uyumlu olan C = 1,5'lik bir kritik hasar sabitini doğrulamıştır. Kesme bölgesi toplam sac kalınlığının yaklaşık %28'ini oluşturmaktadır ve boyutsal doğruluk ölçümleri, P16 delmenin nominal 20 mm'ye en yakın delik çaplarına ulaştığını göstermiştir. AHSS'nin genel davranışına odaklanan önceki çalışmalardan farklı olarak, bu çalışma DP800 delme mekaniği ve yüzey kalitesinin ayrıntılı bir nicel analizini sunmaktadır. Bulgular, takım geometrisi optimizasyonu ve hasar tahmini konusunda yeni bilgiler sunarak, AHSS şekillendirme operasyonlarında üretim hassasiyetini ve süreç güvenilirliğini artırmak için pratik kılavuzlar sunmaktadır.

Anahtar Kelimeler: Çift fazlı çelikler, Zımba ile delme, kesme yüzeyi, FEA.

1. INTRODUCTION

The automotive industry increasingly relies on advanced high-strength steels (AHSS) to reduce vehicle weight and improve fuel efficiency [1–4]. Among these, dual-phase (DP) steels have garnered significant attention due to their superior balance of strength and ductility, as well as their energy absorption capacity. However, as steel strength increases, formability and edge ductility decrease, creating serious challenges for manufacturing operations such as forming, trimming, and punching [5–8]. The cutting and punching processes, commonly used in the production of automotive sheet components, significantly influence the damage-free formability, dimensional accuracy, and service life of AHSS parts [6,9].

Sigvant et al. [8] identified three significant challenges associated with edge fractures in AHSS sheets. The most critical issue is that these cracks are often microscopic

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and difficult to detect during press-line operations. Yet, they can severely compromise the integrity of automotive safety structures in crash scenarios. In addition, such fractures may not appear until late in the design process or even after serial production, making it extremely difficult to implement corrective actions [10]. Consequently, preventing edge cracking requires a deeper understanding of the interplay between material microstructure, edge quality, and tool geometry. For this reason, recent studies have increasingly focused on the technological characteristics of the punching process, particularly the influence of punch-tip design, clearance, and stress triaxiality on fracture initiation and propagation [11,12].

Despite several studies investigating the shearing and edge-crack behaviour of AHSS [8, 10, 13, 14]. A significant deficiency persists in the quantitative evaluation of the punching response of DP800 and its correlation with Cockcroft–Latham (C–L) damage parameters. Research addressing the effect of diverse punch geometries on the local deformation and fracture mechanisms of DP800 remains limited. Previous works by Claver et al. [15] and Myint et al. [16] primarily focused on other AHSS grades; a comprehensive experimental–numerical assessment of DP800 across different punch geometries has not yet been reported. Identifying this research gap forms the primary motivation of the present study.

One of the key requirements in the automotive industry is to reduce component weight without compromising strength and safety, thereby improving fuel efficiency and crashworthiness [17,18]. In this context, dual-phase (DP) steels, composed primarily of ferrite and martensite, offer a favourable combination of low yield strength, high tensile strength, and uniform elongation, making them ideal for forming and punching operations [19]Nevertheless, elevated clearance values reduce the quality. The use of AHSS in automotive body structures has continuously increased over the past four decades, driven by industry demands for lightweight, high-strength solutions [20,21].

The quality of the cut surface plays a critical role in determining component reliability, as defects such as microcracks, delamination, and burrs can initiate early fatigue failure [22,23]. The cutting surface typically consists of four regions—rollover, shear (burnish), fracture, and burr—extending through the sheet thickness [24,25]. The mechanical behaviour of these zones is strongly influenced by tool geometry, stress triaxiality, and clearance. Finite element analysis (FEA) has been widely used to analyse these effects, helping to predict shearing force, sheared-surface length, and localised damage during punching [26]. Increasing the punch angle reduces the required shearing power, whereas excessive clearance can deteriorate edge quality and dimensional precision [27]. Therefore, selecting an appropriate punch-tip form is critical for achieving consistent quality in cutting and piercing operations.

Nevertheless, elevated clearance values reduce the quality of the product's edge [28]. The selection of punch tip form in production is contingent upon the intended use of the resulting parts. Punches with a flat end are generally preferred for cutting operations [12]. Other punch shapes (concave, convex, or inclined) are typically used in piercing operations. It has been observed that the blanking/piercing procedure reduces ductility while increasing hardening, brittleness, and strength, comparable to other cutting operations. A finite element analysis (FEA) can be used to determine the impact of process parameters such as beginning compression, punch and die configuration, on the length of the sheared surface, exerted forces, and part quality.

Although sheet-metal piercing is a well-established manufacturing technique, limited studies have addressed the shear mechanics and surface quality of dual-phase steels in punching applications [29]]. Recent research has focused on optimising punch angles and cutting conditions, reporting that satisfactory surface quality can be achieved at slant angles greater than 10° [14]. Comparative analyses of damage initiation between DP800 and DP1000 steels revealed apparent differences in fracture evolution [30]. Studies using the Johnson–Cook and Cockcroft–Latham models have shown that clearance, punch shape, and shear force are key parameters influencing edge integrity and fracture prevention [30,31]. Furthermore, the effects of stress triaxiality and punch diameter on the sheared-surface length have been reported [31,32]. Collectively, these findings provide a foundation for the present investigation, which aims to extend this understanding to the quantitative prediction of fracture in DP800 punching.

Building upon these earlier studies that clarified the influence of tool geometry and stress triaxiality on punching quality [13,22]. The present work advances the discussion toward a predictive framework based on the Cockcroft–Latham criterion [15, 16, 31–35]. This approach bridges experimental findings with numerical simulation, enabling quantitative evaluation of ductile-fracture evolution in DP800 and establishing a scientific link between surface quality and damage accumulation.

Schenek et al. [33] developed a neural-network-based model using force–displacement curves from drilling various sheet metals. They analysed materials such as DP1200, DP1000, DP800, DP600, HX380LA, DC03, and DX54, and conducted tensile tests to measure tensile strength (Rm), yield strength (Rp0.2), uniform elongation (Ag), and work-hardening exponent (n). These studies provided essential mechanical datasets for evaluating punching-force behaviour and validating damage models for AHSS.

The Cockcroft–Latham (C–L) criterion is widely employed for simulating ductile fracture in cutting and forming processes due to its simplicity and minimal parameter requirement [16,34,35]. It assumes that a fracture occurs when the integral of the maximum

principal stress over plastic strain reaches a critical constant C. Prior studies [15, 16, 31] have validated this approach for AHSS punching and fine-blanking, supporting its use for modelling DP800 fracture behaviour in the present study.

Therefore, this study aims (i) to determine the critical damage constant (C = 1.5) for DP800 dual-phase steel through a combined experimental and numerical approach, (ii) to validate the predictive accuracy of the Cockcroft–Latham damage criterion under different punch geometries (flat, concave, and inclined), and (iii) to examine how punch geometry influences the shear-zone ratio, burr height, and dimensional accuracy of punched holes. The outcomes of this study contribute to the development of a reliable and quantitative framework for correlating tool geometry with ductile-fracture evolution during punching. The findings are expected to provide practical guidelines for optimising tool design and enhancing surface quality in AHSS forming operations, consistent with recent numerical and experimental frameworks proposed by Claver et al. [15], Myint et al. [16], and others [3, 25, 32, 36, 37].

2. MATERIAL and METHOD

2.1. Material

During the experiments, commercially available DP800 steel sheets were employed. Punching samples were prepared by shearing into 100 x 30 mm strips, following the standards outlined in EN ISO 14273. The stress-strain curve illustrated in Fig. 1 was obtained from a tensile test conducted at a grip speed of 2 mm/min to determine the tensile properties. The stress-strain plot of the DP800 sheet steel exhibits the highest true stress value, reaching approximately 900 MPa. Furthermore, it was observed that the material exhibited consistent elongation properties.

Furthermore, the primary structure of DP800 was found to consist of 25% martensite particulate and 75% ferrite phase. The chemical composition of the DP800 material employed in the experimental studies is presented in Table 1.

Table 1. Chemical Composition of DP800 Steel (wt.%).

Mater.	C	Si	Mn	P	Cr	Ni	Mo	Cu
DP800	0.13	0.2	1.53	0.008	0.183	0.05	0.07	0.02

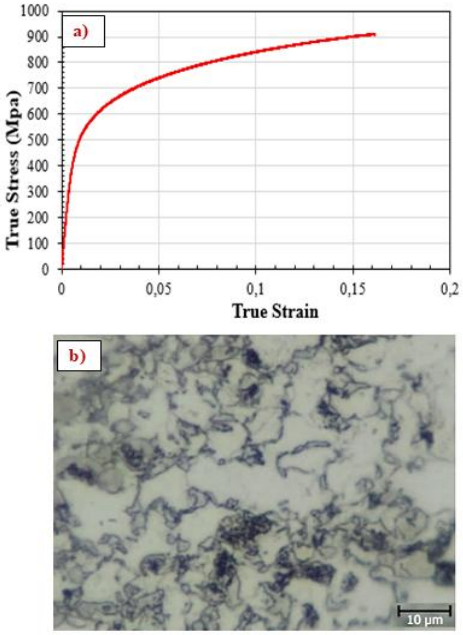


Figure 1. (a) True stress–proper strain curves for DP600/DP800; curves obtained from engineering data with standard transformation and plotted up to the uniform region. (b) Representative microstructure of the same material.

2.2. Punching Process

Hydraulic pressure was employed in punching operations, utilising five distinct punches with varying tip forms (Fig. 2). The velocity and distance between the punch and die (clearance) were maintained at a constant level for all punches used.

Punching experiments were carried out on a DP800 sheet steel with a thickness of 1.5 mm. The tests were performed using the setup illustrated in Fig. 3, which consists of a servo-driven press equipped with a load cell (capacity: 240 kN) and a high-speed data-acquisition (DAQ) system.

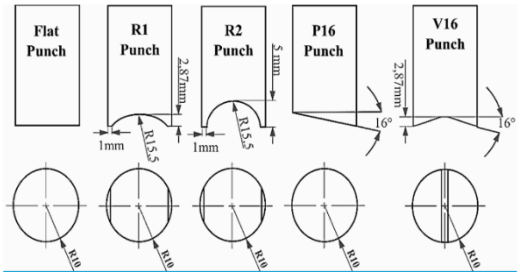
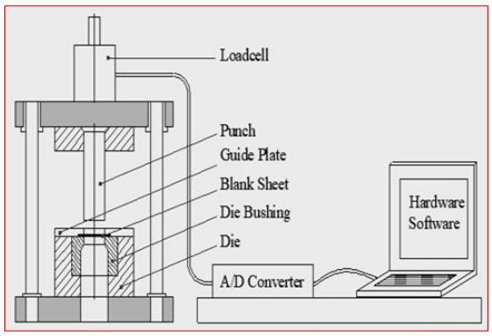


Figure 2. Type of punches used in the experiments.

The DAQ system has a maximum capture capacity of 10,000 samples s-1. In contrast, an effective sampling rate of 2,000 samples s-1 was employed in all tests to ensure stable, low-noise recording and to balance resolution with computational efficiency. The friction coefficient between the punch and the blank was assumed to be 0.1, and the punch speed was maintained at 1.5 mm min-1.



The thickness of the DP800 sheet, t	1.5 mm
The distance between the punch and the die is defined as the clearance, represented by the symbol Cs.	0.07 mm
Punch diameter, D_p	20 mm
Die corner Radius, r_d	0.01 mm
Punch corner Radius, r_p	0.01 mm
Coefficient of Friction (COF)	0.1
Punch speed, V_p	1.5 m/min

Figure 3. Schematic of the punching setup and process parameters (sampling = 2,000 samples s^{-1}; DAQ capacity = 10,000 samples s^{-1}).

The resulting load results of the Punching Experiments were digitised using data cards, amplifiers, load cells, and computer software. The amplified signals were transferred to the connected computer through an analogue-to-digital converter. Before testing, the test apparatus was set up, and the shear forces were determined to match the changes in voltages generated by the load cell.

2.3. Finite Element Analyses (FEA)

The Simufact FEA program was used to determine the material composition for the material model and tensile test models. Experimental tensile test results were compared to those produced from FEA. The validation of the material model is critical for understanding and ensuring the accuracy of the computer-performed piercing process. The axisymmetric model was constructed using 2D rectangular (10) parts to fulfil the study's objectives. Furthermore, the quality of the cut surface was verified using the Cockroft-Latham damage model in the finite element analysis. The piercing test with a flat punch acquired the surface picture for the cut surface deformation and other regions.

3. RESULTS AND DISCUSSION

3. 1. Cutting Surface Properties and Quality

An assessment was conducted to analyse the rollover and braking zones that emerge due to the punching process on DP800 steel, employing the findings of two-dimensional punching simulations and pivotal data. Although using a mesh is more prevalent in two-dimensional finite element analysis, generating more precise results in a shorter time frame is possible. It is crucial to define the damage model to ensure the accuracy of the measurements. The use of finite element analysis enables the application of various damage models, including those validated by Lemaitre, Cockroft-Latham, Oyane, and Johnson-Cook. [34]. The Cockcroft-Latham damage model is one of the most extensively used models described above. Due to its simplicity and the few parameters required, this model is easier to apply than many others. According to this paradigm, damage occurs when stress exceeds the critical damage constant C, as indicated by the calculation below. As a result, mesh separation occurs, causing damage. As a result, the shear damage is clearly visible. In their punching studies, Myint et al. [16] compared various damage models, including Cockroft-Latham [35] and Oyane et al. [34]. The critical damage constant was determined through experimental and simulation-based methods to establish consistency in breakage properties. Moreover, it was established that the importance of C depends on the clearance distance between the punch and die [Eq. 1].

$$\int \frac{\sigma_{max}}{\sigma} \varepsilon \dot{dt} \geq C \qquad (1)$$

The formula σmax indicates maximum principal stress, effective stress, and equivalent total strain.

A comparison was conducted between the experimental data and the simulation experiment results to identify he optimal C constant. The flowchart depicted in Fig. 4 was employed to ascertain a reasonable C value.

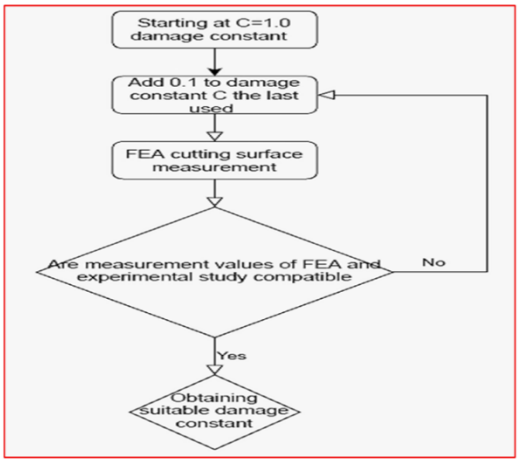


Figure 4. The flow diagram illustrates the method for calculating the Cockroft-Latham constant damage factor

The experimental and simulated cutting profiles of DP800 steel presented in Fig. 5 demonstrate a close correlation between the measured and predicted deformation zones. The rollover and shear regions correspond to initial plastic deformation and localised shearing near the punch edge. In contrast, the fracture and burr zones represent material separation and surface tearing during final penetration. The simulation based on the Cockcroft–Latham criterion (C = 1.5) effectively captured the onset and propagation of fracture, reproducing the relative thicknesses of each zone

(rollover ≈ 0.13 mm, shear ≈ 0.43 mm, fracture ≈ 0.93 mm, burr ≈ 0.07 mm). This strong agreement confirms that the selected damage constant provides a reliable correlation between the experimental and finite-element results, validating the model's predictive capability for DP800 punching behaviour.

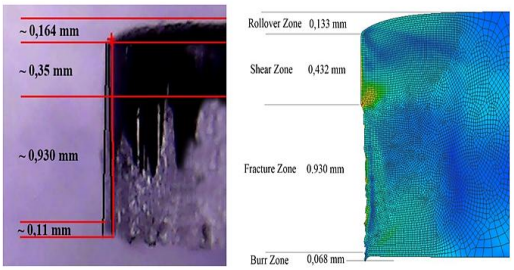


Figure 5. Experimental (a) and simulated (b) cutting surface profiles of DP800 steel punched with a flat tool using the Cockcroft–Latham model (C = 1.5). Four deformation zones are distinguished—rollover (~0.13 mm), shear (~0.43 mm), fracture (~0.93 mm), and burr (~0.07 mm)—showing good agreement between experiment and simulation.

Fig. 6 compares the relative proportions of the deformation zones obtained experimentally and numerically for punches P16 and P0. The experimental results (Fig. 6a) show that the shear zone becomes more pronounced when a flat uncut punch (P0) is used, while the inclined punch (P16) produces a wider rollover region and reduced fracture depth. The numerical predictions (Fig. 6b) display a similar distribution pattern, confirming the close agreement between the finite element simulations and the measured cutting surface morphology. The Cockcroft–Latham damage model (C = 1.5) successfully captured the transition between shear and fracture regions, accurately predicting the overall percentage of each surface zone. Minor differences can be attributed to the mesh's local hardening behaviour and discretisation effects.

This study also highlights the modelling limitations of geometry simplification and mesh dependency. The current finite-element analysis considered a two-dimensional flat-tip P0 punch under symmetric boundary conditions; therefore, the results represent controlled plane-strain conditions. A fully three-dimensional analysis would improve predictive accuracy for punches with complex geometries [38]. Moreover, mesh density significantly affects the computational effort and local strain gradients, indicating that finer meshes enhance precision but increase computation time [28].

The cutting surface properties obtained from punching experiments with a flat punch (Punch) and various punch types were analysed upon examination of Figs. Figures 6a and 6b clearly demonstrate that utilising distinct punch tip types yields different cutting surface deformations and cutting zones. From these results, it can be concluded that the punch's geometry has a significant impact on the deformation of the cutting surface and the formation of shear zones. Moreover, the clearance affects the characteristics of the cutting surface. As the number of clearances is reduced, the shear zone, tipping zone, fracture angle, and burr sizes increase while the fracture zone decreases. This study maintained the clearances at a constant level [36].

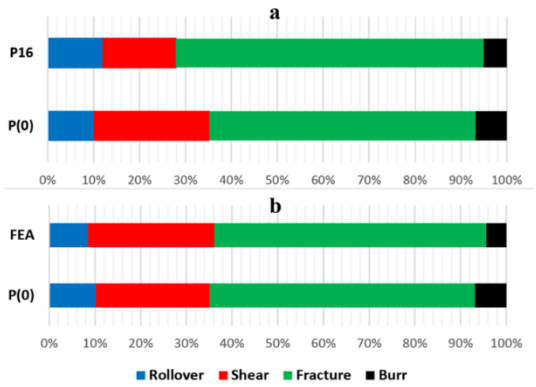


Figure 6. Comparison of cutting surface-zone percentages for punches P16 and P0 obtained from experimental (a) and simulated (b) results.

In general, the objective of puncturing is to achieve the most significant possible cutting area on the cutting surface while simultaneously minimising the burr area. This approach yields a superior-quality cutting surface with minimal roughness. That has a beneficial effect on the performance of the sheet metal part in subsequent forming processes, for example, in terms of the stretchability of the hole and the mechanical stability and damage-free formability of the perforated part. The surface finishes obtained in cutting operations with punch bits of different geometries in this study provide valuable information.

Furthermore, previous studies have demonstrated that clearance can influence the dimensions and characteristics of the zones formed on the cutting surface. That can be optimised independently for each operation. The researchers have elucidated this effect of clearance by indicating that contact between fractured surfaces gives rise to the formation of a secondary polished area [39]. Two-dimensional finite element analysis (FEA) has demonstrated that broken surfaces come into contact with one another.

The cutting process on the surface of punches with inclined geometry is slower due to the cutting angle. That causes crack propagation perpendicular to the punch surface, following the inclination angle [40,41]. In this instance, the degree of deformation increases, and the extent of overturning becomes more pronounced due to the slow cutting process, characterised by a gradual decrease in the distance between the surfaces in contact. This phenomenon can be visualised from the perspective of the overturning zones formed due to punching operations performed with different punches, as illustrated in Figure 7. a. The red arrow indicates the locations where an increase in rollover zones is observed. During punching operations with an inclined punch, it

can be observed that the burned areas formed on some cutting surfaces extend through the entire thickness of the sheet [28,40]. The literature has also demonstrated that this phenomenon can be attributed to the shearing effect of inclined punch geometries with an inclination angle. The elaboration of this study on special material, DP800, provides essential information.

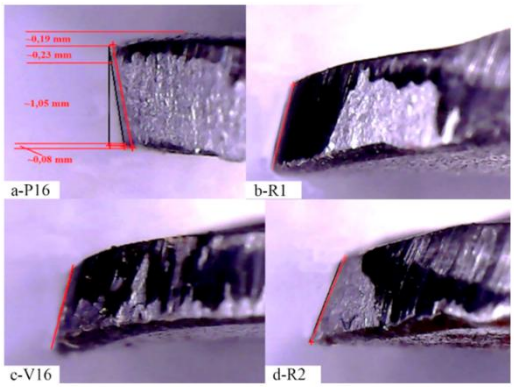


Figure 7. Cutting surface morphologies of DP800 steel obtained using different punch geometries: (a) P16, (b) R1, (c) V16, and (d) R2. shapes

Fig. 5a and 7. illustrate that using an alternative punch geometry markedly alters the cutting surface properties compared to the straight punch, designated as P0. Fig. 8 illustrates the effective-stress fields generated during the piercing of DP800 steel using various punch geometries. The stress concentration near the cutting edge is highest for flat and R2 punches, indicating more localised deformation and a sharper fracture initiation zone. In contrast, V16 and P16 punches show a broader stress distribution and gradual decay along the shearing path, reflecting smoother material separation and reduced strain localisation. The simulation results confirm that punch inclination has a significant impact on the evolution of the stress field and the onset of ductile fracture. A lower stress gradient in inclined punches (V16 and P16) correlates with improved edge quality and lower burr formation, consistent with the experimental observations reported in Fig. 7. [28,42]. Specifically, the burr size resulting from punching with a flat-tipped punch was found to be 0.11 mm, while the burr size resulting from punching using a P16 punch was measured as 0.08 mm.

The following symbols were used: P0, R1, R2, V16, and P16. A proportional comparison of the cutting surface areas resulting from punching with P0 and P16 punches demonstrated that the utilisation of inclined punches markedly increased the burr size. However, the dimensions of the fracture zone increased. As previously stated, the objective is to minimise the dimensions of the fracture zone, as this is the area where cracks typically form on the cutting surfaces. Furthermore, it can be observed that the cutting surface properties demonstrate enhanced homogeneity with the P16 punch, except for the final example, where the slope is reduced. As hole enlargement tests are one of the most common and reliable methods for determining the quality of holes created by punches, it can be suggested that they represent the most appropriate methodology for comparing two punches [11,27,43].

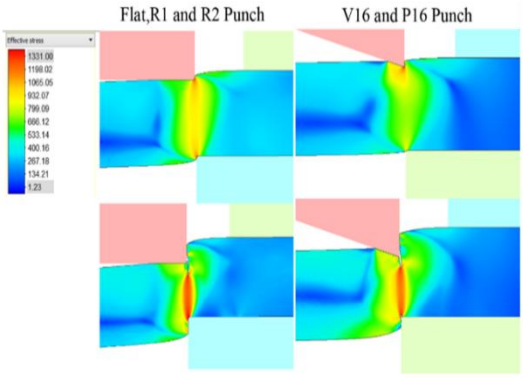


Figure 8. Effective stress distributions obtained from Simufact simulations for different punch geometries: Flat, R1, R2, V16, and P16.

The results of the diameter measurements indicate that the dimensional difference value varies between 〖_(-0.08)^(+0.20)〗 for all punches. Furthermore, as mentioned earlier, the discrepancies according to punch types are illustrated in Fig. 10. As illustrated in Fig. 9, x-y measurements were conducted in parallel with the axes, utilising both x and y approaches in the cut-hole measurement. That was done to ensure precise diameter control.

Upon analysis of Fig. 9, it becomes evident that there is a slight discrepancy in the holes produced with the P16 punch. Furthermore, the most significant discrepancy was noted in the punching operations conducted with alternative punches, followed by those with disparate designs.

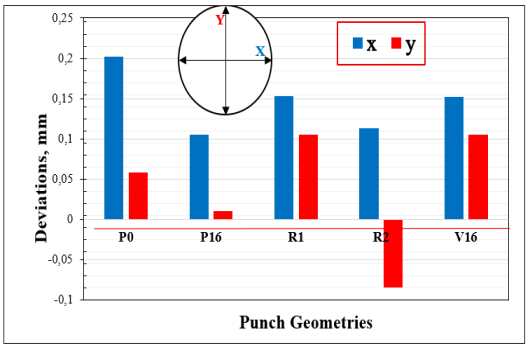


Figure 9. The discrepancies observed can be attributed to inconsistencies in the hole diameter measurements.

A notable discrepancy in dimensional characteristics is evident between the holes produced by a distinct punch with disparate tip geometry [28]. It can be concluded that the dimensional accuracy of hole diameters for DP800 is significantly affected by the geometry of the punch tip. Additionally, Jia et al. [44] employed punches with

varying angles (3°, 7°, and 14°) with AHSS steels. During the investigation, discrepancies were observed in the measurements obtained with punches of differing angles. That was attributed to the springback effect. In addition, it is plausible that the size differences resulting from the recovery of elastic deformation may also be a contributing factor.

4. CONCLUSIONS

In this study, the punching behaviour of DP800 dual-phase steel was investigated through both experimental trials and finite element simulations using the Cockcroft–Latham damage model. The results revealed that punch geometry has a significant influence on the formation of shear zones, burr height, and the propagation of fractures. Specifically, the P16 punch yielded the smoothest cutting surface and lowest punching force, indicating its suitability for high-precision applications. The damage constant (C = 1.5) derived from simulations strongly agreed with experimental observations, validating the model's predictive capability. The dimensional accuracy of the punched holes was also highly dependent on the punch tip design, with the P16 punch producing hole diameters closest to the nominal value of 20 mm. These findings contribute to a deeper understanding of punching mechanics in AHSS materials and provide practical guidance for optimising tool design in automotive manufacturing [45].

- The results of the 2D simulation tests effectively determined the critical damage constant for the DP800 steel sheet. According to these results, the thickness of the shear zone between the overturning and the onset of fracture was 28% of the total thickness.
- Plain and P16 punches appear to be the favourites for producing the smoothest cut surfaces compared to the others. Punching with the P16 punch also produced the lowest punching force.
- The utilisation of disparate punch geometries has been demonstrated to influence the distribution of stress and the formation of fractures. Furthermore, it has been established that the cutting surface area of the punch tip exerts an influence on the punch force.
- The hole sizes most closely approximating the nominal size of 20 mm were produced with the P16 punch.

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DECLARATION OF ETHICAL STANDARDS

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AUTHORS' CONTRIBUTIONS

Bilge DEMIR: Concept and design of the study, supply of materials, management of the study, analysis and article writing.

Abdulsalam, Elamen SAIER: He conducted the experiments and wrote them as his master's thesis.

Hakan GÜRÜN: He executed and oversaw the punch operations and conducted FEM analysis.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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