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An in-depth study on the impact of test parameters on the erichsen index and punch force

Test parametrelerinin erichsen sabiti ve zımba kuvvetine etkisinin derinlemesine incelenmesi

Yazar(lar) (Author(s)): *Fatih CİVELEK*[1], *Ahmet ÖZDEMİR*[2]

ORCID[1]: *0000-0001-6397-3836*

ORCID[2]: *0000-0001-9919-8149*

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An In-Depth Study on the Impact of Test Parameters on the Erichsen Index and Punch Force

Highlights

- *The impact of sheet thickness, punch velocity, and punch diameter on the Erichsen Index, punch force, and fracture strains was investigated.*
- *The influence of the die bore radius to punch radius (R_D/R_P) ratio on effective strains and the Erichsen Index was examined.*
- *It has been found that the influence of sheet thickness on the Erichsen Index and fracture strains becomes more significant as the punch diameter decreases.*
- *It was observed that the punch force increased almost linearly as both sheet thickness and punch diameter increased.*

Graphical Abstract

Deformations of sheet metal samples were studied during the Erichsen test. The variation in effective strain with respect to the contact angle, as well as the changes in effective strain values at the onset of crack formation due to variations in punch diameter, were presented.

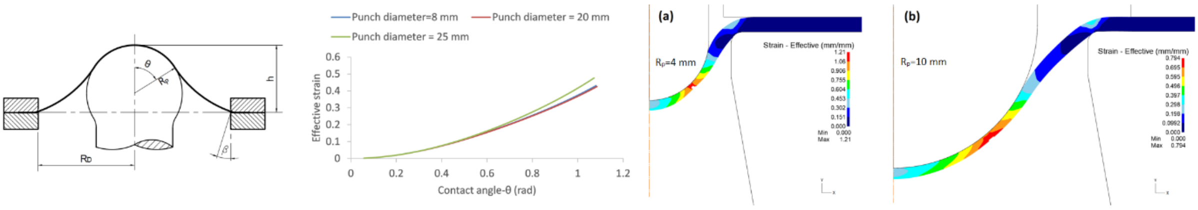

Figure. Effective strains obtained during the Erichsen test

Aim

The objective of this research is to explore the effects of test parameters on the Erichsen Index, punch force, and fracture strain.

Design & Methodology

Experiments were designed with Taguchi method and the contributions of the parameters to the results were obtained with ANOVA. Simulations were carried out with the help of fracture strains obtained from experimental data and theoretical solutions.

Originality

Although numerous studies in the literature explore the impact of sheet thickness and punch diameter on the Erichsen Index, no experimental study has been found that investigates how the sheet metal thickness/punch radius and R_D/R_P ratios influence the EI value and effective strains. Furthermore, no study was found in the literature that derived effective stress-effective strain curves from punch force-punch displacement data obtained from Erichsen tests on DC04 steel sheets.

Findings

The effective strain is influenced only by the contact angle and the R_D/R_P ratio, and the strain values increase with the increasing R_D/R_P ratio. It has been observed that larger contact angles, and thus higher fracture strains, are achieved with a reduction in punch diameter and a rise in sheet thickness. The fracture strains of the sheets under friction were estimated using equations derived for the ideal frictionless case. It was observed that the simulations performed using these fracture strains closely matched the experimental results, with the Mean Absolute Percentage Error (MAPE) not exceeding 3.5%.

Conclusion

It was observed that both the Erichsen Index and the punch force increased nearly linearly with the rise in punch diameter. Additionally, it was determined that the effect of sheet thickness on EI grew with the decrease in punch diameter, resulting in larger fracture strains.

Declaration of Ethical Standards

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

An In-Depth Study on the Impact of Test Parameters on the Erichsen Index and Punch Force

Araştırma Makalesi / Research Article

Fatih CİVELEK[1*], Ahmet ÖZDEMİR[2]

[1]Graduate School of Natural and Applied Sciences, Gazi University, Ankara, 06500, Turkiye
[2]Faculty of Technology, Gazi University, Ankara, 06500, Turkiye

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ABSTRACT

In this paper, the Erichsen index (EI) values of the DC04 steel sheets were obtained both experimentally and through finite element analysis. The influences of punch size, punch speed, and thickness level of the sheet on the punch force, EI and fracture strains were examined. The design of the experiments was created using the Taguchi L9 orthogonal array, and the influences of the factors on the EI value were detected numerically with an analysis of variance (ANOVA). It was observed that the most effective parameter on the EI is the punch diameter. Additionally, it was noticed that the fracture strain and the Erichsen index increased with higher levels of thickness, and the punch speed showed no appreciable impact on the EI value. It was found that as the punch diameter decreased, the impact of sheet thickness on ES and fracture strain increased. The punch force increases almost linearly with both the punch diameter and sheet thickness. The effective strains at the onset of crack formation were calculated mathematically, and simulations were conducted based on these data. The simulation results of the Erichsen tests show strong consistency with the experimental findings, with the Mean Absolute Percentage Error not exceeding 3,5%.

Keywords: Erichsen cupping test, sheet metals, finite element method.

Test Parametrelerinin Erichsen Sabiti ve Zımba Kuvvetine Etkisinin Derinlemesine İncelenmesi

ÖZ

Bu makalede, DC04 çelik sacların Erichsen Sabiti (ES) değerleri hem deneysel yöntemle hem de sonlu elemanlar analizi ile elde edilmiştir. Zımba çapı, zımba hızı ve sac kalınlığının zımba kuvvetine, ES ve kırılma gerinimi üzerine etkileri incelenmiştir. Deneylerin tasarımı Taguchi L9 ortogonal dizisi kullanılarak oluşturulmuş ve faktörlerin ES değeri üzerindeki etkileri varyans analizi (ANOVA) ile sayısal olarak tespit edilmiştir. ES değerini etkileyen en önemli parametrenin zımba çapı olduğu görülmüştür. Ayrıca, kırılma geriniminin ve Erichsen değerlerinin sacın kalınlaşmasıyla arttığı ve zımba hızının ES değerine önemli bir etkisinin olmadığı görülmüştür. Sac kalınlığının ES ve kırılma gerinimi üzerine etkisinin zımba çapının küçülmesiyle arttığı tespit edilmiştir. Zımba kuvvetinin hem zımba çapı hem de sac kalınlığıyla neredeyse lineer olarak arttığı gözlemlenmiştir. Çatlak oluşumu başlangıcındaki efektif gerinimler matematiksel olarak hesaplanmış ve bu veriler yardımıyla simülasyonlar gerçekleştirilmiştir. Erichsen testlerinin simülasyon sonuçları deneysel bulgularla güçlü bir tutarlılık göstermiştir ve Ortalama Mutlak Yüzde Hata %3,5'i geçmemektedir.

Anahtar Kelimeler: Erichsen şişirme testi, sac metaller, sonlu elemanlar yöntemi.

1. INTRODUCTION

In recent years, DC series steel sheet materials have frequently been preferred in the automotive industry owing to their extremely good formability [1-3]. For sheet metals, formability is commonly described as the sheet material's capability to deform into the intended form devoid of tearing or necking [4]. Knowing the deformability capabilities of sheet materials is critical for successfully manufacturing sheet metal items [5]. The Erichsen cupping test is frequently preferred to determine deformability characteristics and measure sheet metal's stretch-forming capacity in biaxial tension. During the Erichsen test, the sheet sample is clenched between the matrix and the holder plate to prevent the sheet from sliding and flowing into the deformation zone [6]. In the Erichsen test, the blank is drawn until a wide enough crack extending across the whole thickness of the sheet appears, and the bulging depth is measured at the moment the crack comes into view. This depth corresponding to the path taken by the punch up to which the fracture emerges is defined as the Erichsen index (EI) [7]. There are many papers in the literature examining the influences of test parameters on the Erichsen index. Gao et al. [8] examined the forming capacity of composite sheets consisting of polyether ether ketone matrix and carbon fiber reinforcement materials at different temperatures and punch speeds. It has been ascertained through Erichsen cupping tests that the impact of temperature on the deformability of the composite sheets is more remarkable than the punch velocity. Following the tests performed at 325 °C, it was observed that the Erichsen index decreased by only 5% as the punch velocity was raised from 2 mm/min to 120 mm/min. Kang et al. [9] examined the deformation behavior of

*Sorumlu Yazar (Corresponding Author)
e-posta : fatihcivelek@cumhuriyet.edu.tr

AZ61 magnesium metal sheet samples prepared via the friction stir operations using the Erichsen test. Researchers have noted a decline in the EI value as punch speed increases. It was noted that the EI decreased from 3.7 mm to 2.1 mm, with the punch velocity rising from 0.1 mm/min to 10 mm/min. The impact of the deformation rate on the formability of metal sheets varies based on the material type [10, 11], microstructure [12, 13], and stress state [14, 15]. Although the formability of DC04 steel related to deformation rate has been investigated through methods like the uniaxial tensile test [16], no study has been found in the literature examining the impact of punch velocity on the Erichsen index of DC04 sheets. Another significant parameter affecting formability is sheet thickness. Numerous studies have shown that greater sheet thickness leads to a higher Erichsen index. [17-21]. Reddy et al. [17] investigated the forming abilities of stainless steel, copper, brass, and aluminum sheet materials with different thicknesses via Erichsen tests. Erichsen tests were performed using grease, castor oil, and lanthax grease lubricants. It was noted that the EI value exhibited an increase as the sheet thickness increased. Under the dry condition, it was observed that the EI value increased by 30%, 27.4%, 38.9%, and 74.7% for the copper, stainless steel, brass, and aluminum sheets, respectively, when the sheet thickness ranged from 0.3 mm to 1.0 mm. Also, it has been found that using lubricants increased the Erichsen index, and grease was the oil that increased the EI value the most compared to castor oil and lanthax grease. Kamikawa and Morino [22] examined the influences of blank thickness as well as punch size on the force-distance diagrams obtained via the Erichsen test. In view of Erichsen experiments, it was asserted that the punch force and EI value of low carbon steel sheet material increased with increasing punch size and blank thickness. They stated that the EI rises linearly as the punch diameter increases, while blank thickness mainly affects the displacement following local necking (nonuniform). Cakis et al. [23] examined the effects of punch speed as well as punch diameter on the formability of Al1050 aluminum sheets. Erichsen tests were conducted with spherical punches of 8, 15, and 20 mm diameter at 5, 6.25, and 8 mm/min punch speeds. It has been asserted that a larger punch size results in a greater Erichsen index. In the experiments conducted with the 20 mm punch diameter, a reduction in the EI value was detected with a rise in the punch velocity. However, in the tests accomplished with the punch of 8 mm diameter, it was seen that the largest Erichsen index was reached at the punch speed of 6.25 mm/min.

The literature review indicated that while there are studies exploring the influences of sheet thickness and punch size on the Erichsen index, no research has addressed the effect of the sheet thickness/punch radius ratio on the EI value. However, it is essential to design forming tools with radii suitable for sheet metal thickness in industrial applications. Additionally, no experimental study has been found in the literature examining how the ratio of the die bore diameter to the punch diameter in the Erichsen test setup affects the Erichsen index and effective strains. Therefore, in this paper, the impact of punch speed, sheet thickness, punch diameter, and sheet thickness/punch radius ratio on the Erichsen index of DC04 steel sheets was investigated experimentally. Additionally, fracture strain values were computed using the data obtained from the Erichsen tests, and simulations were performed using the normalized Cockcroft and Latham damage criterion. This study provides valuable data that could lead to a more comprehensive understanding of how these parameters affect the material forming process. Additionally, by deriving effective stress-effective strain curves from punch force-punch displacement data obtained from Erichsen tests on DC04 steel sheets, the research helps advance the understanding of material behavior during forming processes, offering insights for optimizing manufacturing parameters. The findings of this study could guide automotive manufacturers in determining the optimal thickness of DC04 steel, achieving an optimal balance between formability and weight. This would result in lighter and efficiently formed parts, leading to significant cost savings.

2. MATERIAL AND METHOD

2.1. Materials

In the experiments, 0.5 mm, 0.8 mm, and 1.0 mm thick DC04 steel sheet specimens were used. The characterization test of sheet materials was carried out by the Bruker Q4 TASMAN optical emission spectrometer, and the elemental compositions of the steel sheets obtained from the tests are displayed in Table 1.

Table 1. Elemental composition of steel sheets (weight %)

Elements	C	Si	Mn	P	S	Al	Fe
% weight	0.072	<0.01	0.197	<0.005	<0.002	0.029	99.43

2.2. Tensile Tests

Uniaxial tensile tests were conducted to ascertain the mechanical behavior of the materials. The test samples were prepared using wire electrical discharge machining. The tests followed the ISO 6892-1:2009 standard, and the dimensions of the specimens are depicted in Figure 1.

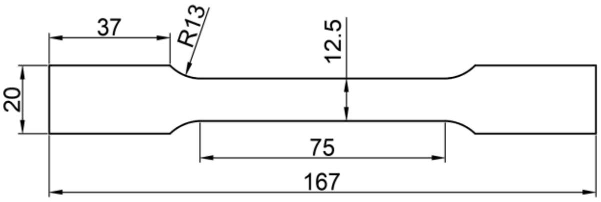

Figure 1. Dimensions of the tensile test sample (in mm) as per ISO 6892-1:2009 standards

Steel sheet samples, obtained via cutting the sheets along the rolling direction (0°), diagonal (45°), and transverse direction (90°), were tested using the Utest brand testing device, with a crossheading velocity of 1 mm/min.

2.3. Erichsen Cupping Experiments

Erichsen experiments were conducted with a specially manufactured, fully automated Erichsen test machine [23] without lubrication, and each experiment was repeated three times. The machine can apply a blank holder load up to 50 kN, and the punch velocity can be adjusted up to 100 mm per minute. Punches with diameters of 8 mm, 20 mm, and 25 mm were utilized in the tests. A schematic representation of the standard Erichsen experimental setup for a punch of 20 mm diameter is given in Figure 2. The bore diameters of the dies and blank holders used according to different punch diameters (P_D) in the Erichsen tests are given in Table 2. All of the sheet metal samples used in the Erichsen experiments were sizes of 90 mm x 90 mm.

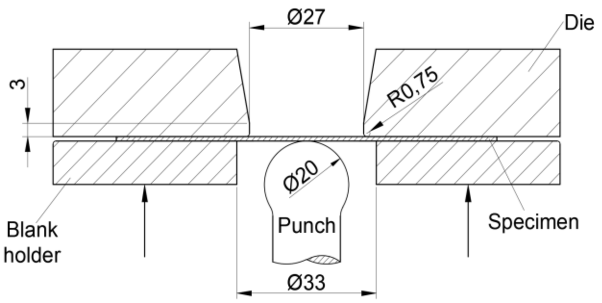

Figure 2. The illustration of the Erichsen experimental setup

Table 2. Dimensions of the Erichsen test apparatus

Die-set No.	Punch diameter-P_D (mm)	Blank holder bore diameter-BH_D(mm)	Die bore diameter-DB_D (mm)
1	8	10	11
2	20	33	27
3	25	40	40

The Taguchi method is a statistical technique that optimizes experimental design by reducing time and effort [24]. This approach allows for the analysis of interactions between multiple factors while minimizing the number of experiments [25]. Hence, the Taguchi L9 orthogonal array was utilized in the experimental design, and parameters of sheet thickness, punch speed, and punch diameter, each with three levels, were chosen (Table 3). In addition, the blank holder load of 10 kN remained constant throughout all of the experiments in accordance with the ISO 20482:2013 standard.

Following the Erichsen experiments, Taguchi analyses were performed via the Minitab program to examine the effects of the parameters (punch diameter, sheet thickness, and punch speed) on the EI and the punch loads. Materials with a larger Erichsen index exhibit greater formability. Therefore, during the analysis, the 'Larger is better' option was chosen for the signal-to-noise (S/N) ratios of the EI values. After the Taguchi analyses, analysis of variance (ANOVA) tests were performed using a confidence level of 95% and a significance level of 5%.

Table 3. Factors and their levels in the Erichsen tests

Parameters	Material	Levels		
		1	2	3
Sheet thickness (mm)		0.5	0.8	1
Punch velocity (mm/s)	DC04	0.1	0.4	1
Punch diameter (mm)		8	20	25

2.4. Simulations of Erichsen Experiments with Finite Element Method

Simulations were conducted using the same parameter values as those used in the Erichsen experiments designed with the Taguchi method. In the simulations, a friction coefficient of 0.3 was set for the interaction between the punch and the blank, considering the studies conducted under dry friction conditions [26]. The tools were modeled as analytical rigid (Figure 3), and sheets were considered to be isotropic. Structural quadrilateral mesh was used in the simulations. The specifications of the apparatus and workpiece used in the simulation are provided in Table 4. The workpiece, die, blank holder, and punch were modeled in 2D using SolidWorks software and saved in the DXF file format. These files were then imported into Deform-2D software to create the simulations. Since the die, blank holder, and punch were treated as rigid bodies, no material assignment or meshing was required. The workpiece was defined as isotropic plastic, and the material assignment was made using the material library of Deform-2D software.

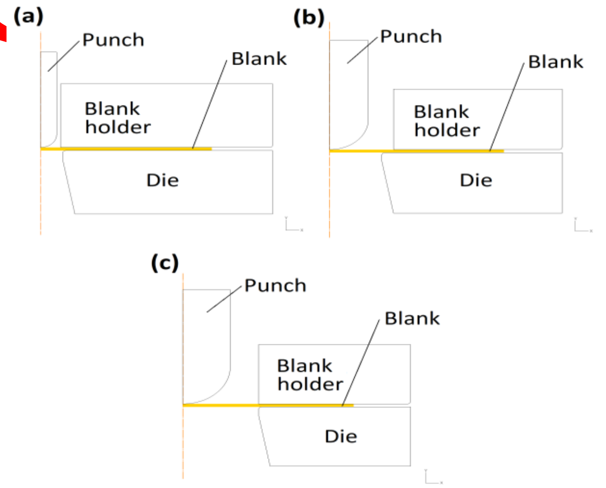

Figure 3. Simulation designs for the different die sets with Deform 2D; a) P_D = 8 mm, b) P_D = 20 mm, c) P_D = 25 mm

Table 4. Properties of the apparatus and workpiece utilized in the simulations

Apparatus and workpiece	Material	Structure	Mesh	Software
Punch	-	Analytical rigid	-	Deform-2D
Blank holder	-	Analytical rigid	-	
Die	-	Analytical rigid	-	
Workpiece	DC04 steel	Isotropic plastic	Quadrilateral	

Simulations were conducted using the 1 mm thick sheet and the 8 mm diameter punch with varying numbers of finite elements to evaluate the dependence of the simulation results on the number of elements. Initially, 40 elements were used, and the number was gradually increased. With 40 elements, the EI value was recorded as 6.99 mm. As the number of elements exceeds 4000, the Erichsen index converges to 5.54 mm (Figure 4). Consequently, the optimal number of elements was established as 4000.

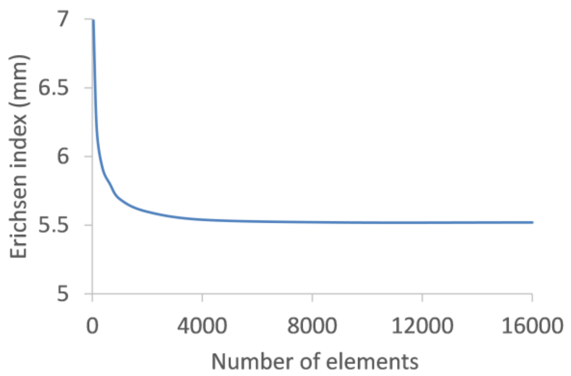

Figure 4. Dependence of the Erichsen index on the number of elements

Normalized Cockcroft & Latham damage criterion was used in the simulations to estimate the ductile fracture characteristics of the DC04 steel sheet. According to this criterion, Critical Damage Value (CDV) is calculated using the formula given in Equation 1.

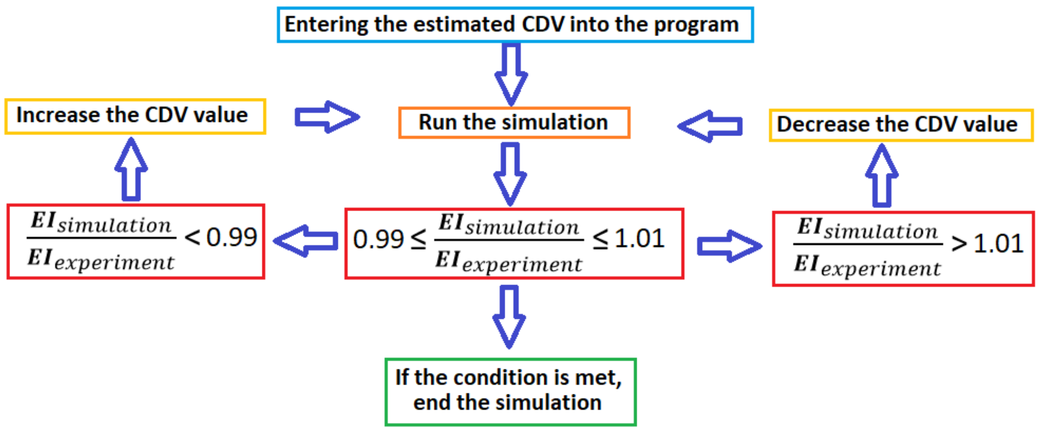

Figure 5. Schematic depiction of determining the CDV value in the simulations

$$CDV = \int_0^{\bar{\varepsilon}_f} \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon} \quad (1)$$

Here, σ*is the largest principal tension; $\bar{\sigma}$ is the effective stress, and $\bar{\varepsilon}$ is the effective strain.

For determining the CDV, Erichsen experiments performed with the punch of 20 mm diameter were taken into account, and the simulations were repeated until the Erichsen index values acquired in the simulations were sufficiently close to the values obtained in the experiments (Figure 5).

The CDV values for the 0.5 mm, 0.8 mm, and 1.0 mm thick DC04 steel sheets were found to be 0.622, 0.723, and 0.817, respectively. Afterward, the effective strains at the moment of fracture were calculated for all of the Erichsen experiments using analytical solutions formulated for the ideal frictionless case [27]. Since effective stresses are equal to the principal stresses in isotropic sheet materials [28], it can be assumed that the CDV value is identical to the fracture strain when Equation 1 is considered. Thus, the CVD values obtained from simulations using the 20 mm diameter punch were compared with the theoretically calculated fracture strains. It was found that the fracture strains for the sheets with thicknesses of 1 mm, 0.8 mm, and 0.5 mm under friction could reach up to 75%, 73%, and 68% of the values in the frictionless case, respectively. These percentages were utilized to calculate CVD values for the other Erichsen experiments, and these CDV values were integrated into the simulations.

Based on the data collected from the experiments and simulations, the Mean Absolute Percentage Error (MAPE) was computed using Equation 2.

$$MAPE = \frac{100\%}{n} \sum_{i=1}^{n} \frac{|Xs_i - Xe_i|}{Xe_i} \quad (2)$$

Xs and Xe denote the values obtained from simulations and experiments, respectively, while n indicates the total number of experiments conducted.

3. RESULTS AND DISCUSSION

The engineering stress-strain curves of the steel sheets with thicknesses of 0.5 mm, 0.8 mm, and 1 mm obtained by the experiments are given in Figure 6.

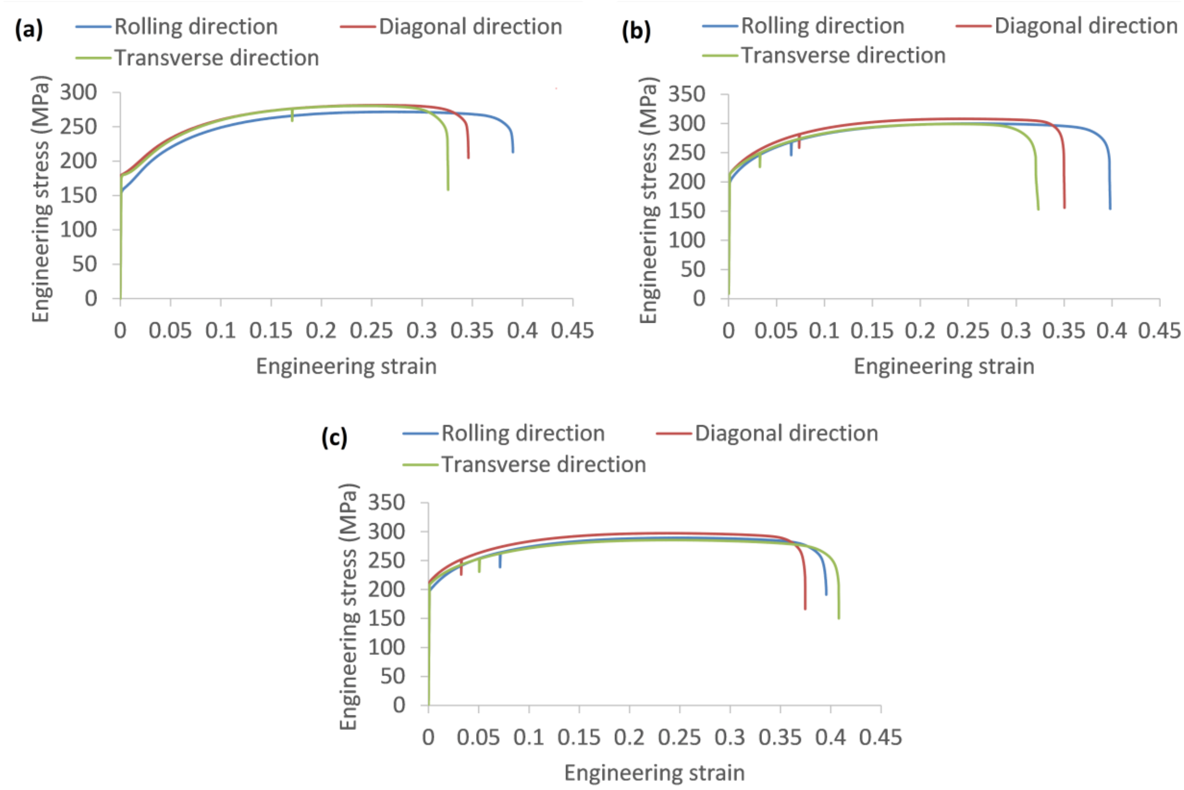

Figure 6. Engineering stress-strain curves of sheet materials; a) 0.5 mm DC04 sheet material, b) 0.8 mm DC04 sheet material, c) 1.0 mm DC04 sheet material

Table 5. Results obtained from the uniaxial tensile tests conducted on the DC04 sheet metals.

Sheet thickness (mm)	Angle from the rolling direction	Yield stress (MPa)	Ultimate tensile stress (MPa)	Total Elongation (%)
0.5	0°	156	272	39
	45°	182	281	34.6
	90°	181	280	32.5
0.8	0°	199	300	39.8
	45°	214	308	35
	90°	216	299	32.3
1	0°	198	289	39.5
	45°	215	297	37.4
	90°	210	286	40.8

The uniaxial tensile test results for the DC04 sheet metals are detailed in Table 5. It was seen that the maximum elongations of the 0.5 mm and 0.8 mm thick steel sheets were in the rolling direction. However, the 1 mm thick sheet elongated more in the transverse direction, and the elongations of the steel sheets for all of the thicknesses in the rolling direction were measured to be approximately 40%.

It was observed that the punch force increased as the punch advancement progressed, followed by a sudden decrease due to necking (Figure 7). As the punch advanced, the deformation, effective strain, and corresponding effective stress in the sheet metal samples increased, leading to a rise in punch force. However, after necking, despite the continued increase in stress and strain, the rapid thinning of the sheet reduced the deformed cross-sectional area, resulting in an instant reduction of the punch force.

EI values and the maximum punch loads obtained from the Erichsen cupping experiments are given in Table 6. As a result of the tests conducted with the punch of 20 mm diameter, it was seen that the EI values found for the DC04 sheets were consistent with the literature. Jasinski et al. [21] stated that the Erichsen index values of DC04 steel sheets were found to be 11.46 mm for the thickness of 1.0 mm and 10.98 mm for the thickness of 0.8 mm in their study. Diegelmann et al. [29] found the EI value to be 11.3 mm for the 1 mm thick DC04 sheet materials, and Burdek [30] claimed that the Erichsen index was detected to be 10.4 mm for the 0.8 mm thick DC04 sheet.

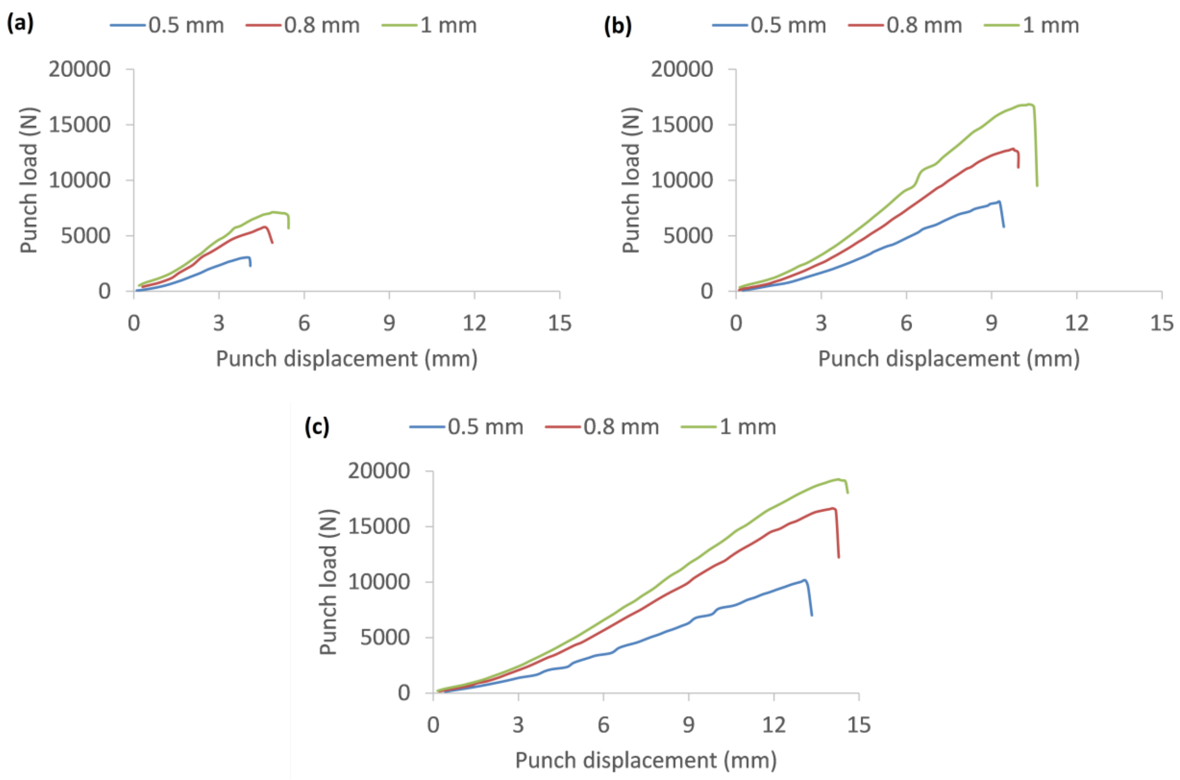

Figure 7. Displacement-Punch force curves of the DC04 steel sheets for various thicknesses; a) the P_D = 8 mm, b) the P_D = 20 mm, c) the P_D = 25 mm

Table 6. Erichsen test results for the steel sheets

Experiment No.	Sheet Thickness (mm)	Punch Speed (mm/s)	Punch Diameter (mm)	Erichsen Index (mm)	Maximum Punch Force (N)
1	0.5	0.1	8	4.1013	3067
2	0.5	0.4	20	9.4257	8060
3	0.5	1	25	13.3339	10167
4	0.8	0.1	20	9.9375	12840
5	0.8	0.4	25	14.281	16640
6	0.8	1	8	4.8763	5717
7	1	0.1	25	14.5968	19259
8	1	0.4	8	5.4482	7133
9	1	1	20	10.6003	16855

Table 7. Analysis of Variance table for the Erichsen index

Factors	DF	Sum of square	Mean square	F-Value	P-Value	Contribution
Sheet thickness (mm)	2	3.082	1.5412	10.78	0.085	2.18%
Punch speed (mm/s)	2	0.581	0.2904	2.03	0.33	0.41%
Punch diameter (mm)	2	137.761	68.8803	481.69	0.002	97.21%
Error	2	0.286	0.143			0.20%
Total	8	141.71				100.00%

In this study, the EI values were measured to be 10.6 mm for the 1.0 mm thick DC04 steel sheets and 9.94 mm for the 0.8 mm thick sheets when the punch of 20 mm diameter was utilized. Considering ANOVA and Taguchi analyses, it is discovered that the factor increasing the EI of the steel sheets the most is the punch diameter (Table 7). Moreover, the EI value increases, albeit slightly, with increasing sheet thickness (Figure 8-9), and the P-value of 0.33 indicates that punch speed has no meaningful influence on the EI.

As shown in Table 8 and Figure 10-11, the punch diameter is the key parameter influencing the punch force. The sheet thickness has a far greater impact on the maximum punch force than it does on EI. Within the chosen range of punch speed, punch velocity does not have a noticeable effect on the punch force.

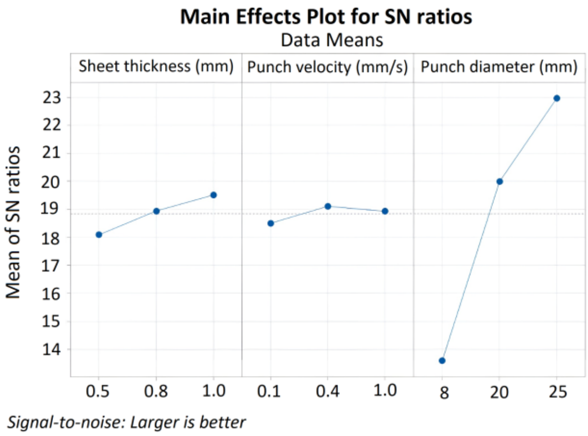

Figure 8. S/N ratios acquired via the Taguchi analysis on the EI of the steel sheets

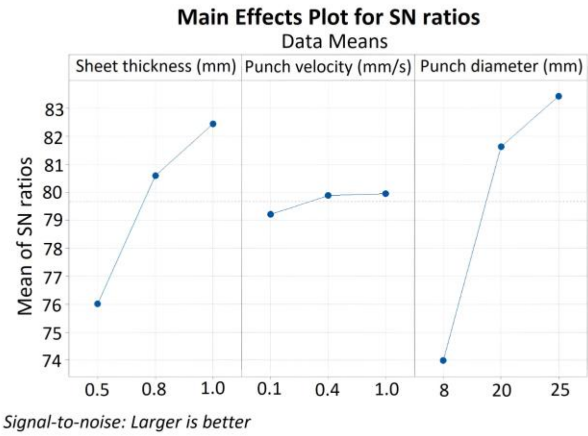

Figure 10. S/N ratios acquired via the Taguchi analysis on the maximum punch force

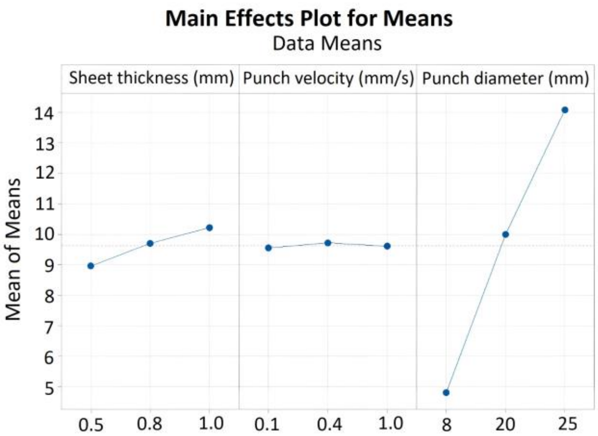

Figure 9. Means of EI values acquired via the Taguchi analysis

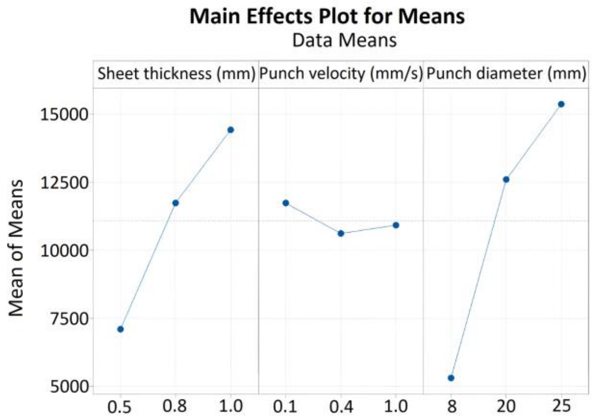

Figure 11. Means of maximum punch forces acquired via the Taguchi analysis

Table 8 Analysis of Variance table for the maximum punch load

Factors	DF	Sum of square	Mean square	F-Value	P-Value	Contribution
Sheet thickness (mm)	2	65.719	32.8595	818.94	0.001	30.23%
Punch speed (mm/s)	2	1.006	0.5031	12.54	0.074	0.46%
Punch diameter (mm)	2	150.578	75.2892	1876.39	0.001	69.27%
Error	2	0.08	0.0401			0.04%
Total	8	217.384				100.00%

To gain a deeper understanding of how the punch diameter and sheet thickness affect the EI, a theoretical solution for a frictionless case, as outlined in the literature [27], was utilized. Figure 12 illustrates the contact angle (θ), punch displacement (h), and the angle formed by the surface normal at the boundary (β) during the Erichsen test. R_P and R_D denote the punch radius and die bore radius, respectively.

Chakrabarty [27] derived the following equations that describe the correlation between punch displacement and the contact angle.

$$\sin\beta = \frac{R_P}{R_D}\sin^2\theta \tag{3}$$

$$h = R_P\{(1-\cos\theta) + sin^2\theta\; ln\frac{\tan(\theta/2)}{\tan(\beta/2)}\} \tag{4}$$

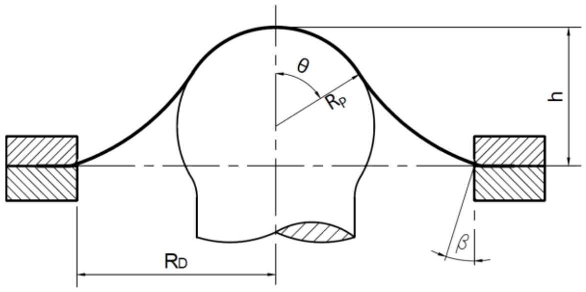

Figure 12. Deformation geometry during the Erichsen test

In the frictionless case, maximum thickness reduction occurs at the pole, and the sheet thickness at this location can be determined using Equation 5. In this equation, t_i denotes the initial sheet thickness, while t_p represents the sheet thickness at the pole [27].

$$t_p = \frac{t_i(1+\cos\theta)^4}{4(1+\cos\beta)^2} \qquad (5)$$

The maximum effective strain ($\bar{\varepsilon}_{max}$) in the frictionless case can be calculated using Equation 6.

$$\bar{\varepsilon}_{max} = \ln\left(\frac{t_i}{t_p}\right) = \ln\left(\frac{4(1+\cos\beta)^2}{(1+\cos\theta)^4}\right) \qquad (6)$$

Equation 8 demonstrates how the punch force varies with punch diameter, equivalent stress ($\bar{\sigma}_\theta$), and sheet thickness (t_θ) at the contact boundary. Additionally, the effective strain at the contact boundary ($\bar{\varepsilon}_\theta$) can be calculated by Equation 9.

$$t_\theta = t_i\left[\frac{1+\cos\theta}{1+\cos\beta}\right]^2 \qquad (7)$$

$$P = 2\pi R_p t_\theta \bar{\sigma}_\theta \sin^2\theta \qquad (8)$$

$$\bar{\varepsilon}_\theta = \ln\left(\frac{t_i}{t_\theta}\right) = 2\ln\left(\frac{1+\cos\beta}{1+\cos\theta}\right) \qquad (9)$$

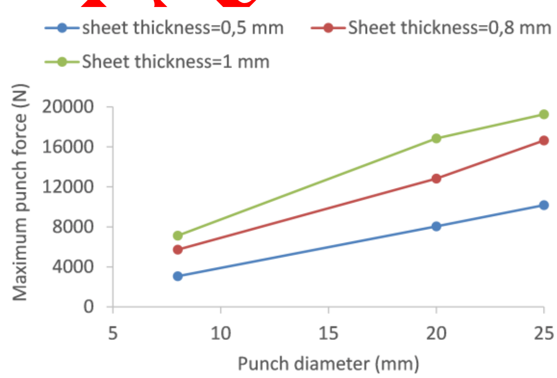

Figure 13. Impact of varying punch diameters on the maximum punch force

When Equations 7 and 8 are considered, it is clear that the punch load rises linearly with both the initial sheet thickness and punch diameter. However, due to work hardening and friction, the variation in maximum punch load with respect to sheet thickness and punch diameter deviates slightly from linearity (Figure 13 -14).

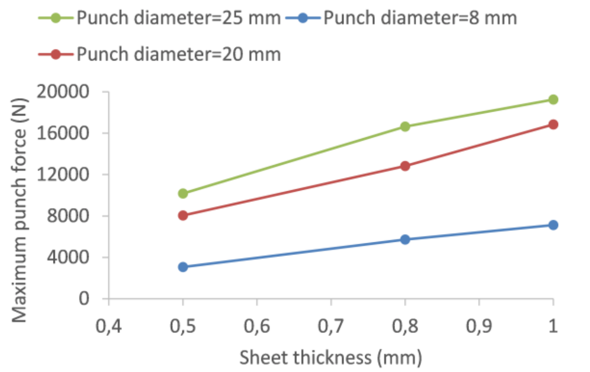

Figure 14. Impact of varying sheet thicknesses on the maximum punch force

The punch velocity influences the punch load by altering the effective stress. However, this effect is relatively small compared to the impacts of punch diameter and sheet thickness. As a result, the effect of punch speed on punch force was found to be only 0.46% in the ANOVA results. To more clearly visualize the effect of punch speed, force-displacement graphs obtained from Erichsen experiments, along with the above equations, were used to generate effective stress-effective strain curves (Figure 15).

As shown in Figure 15, the stresses at the initial strain values are inaccurate. At the beginning of the Erichsen experiments, the bending effect is significant and cannot be ignored. Due to bending, compressive stresses develop on the side of the sheet in contact with the punch, while tensile stresses appear on its outer surface (Figure 16). As the punch advances further, the bending effect diminishes, and the stresses calculated using Equation 8 become more accurate. The influence of bending decreases as the ratio of punch radius to sheet metal thickness (R_p/t_i) increases. For the punch diameter of 8 mm, reasonable stress values were obtained once the effective strain exceeded 0.1, while for the punch diameter of 25 mm, stress values became reliable when the strain surpassed 0.03. Additionally, the calculated effective stresses are slightly higher than expected due to the friction, which increases the punch force. Although it is challenging to discern the influence of punch velocity on the effective stress because of the combined influence of friction and bending, as seen in Figure 15, rising punch speed did lead to a slight increase in effective stress values, likely attributed to the work hardening effect.

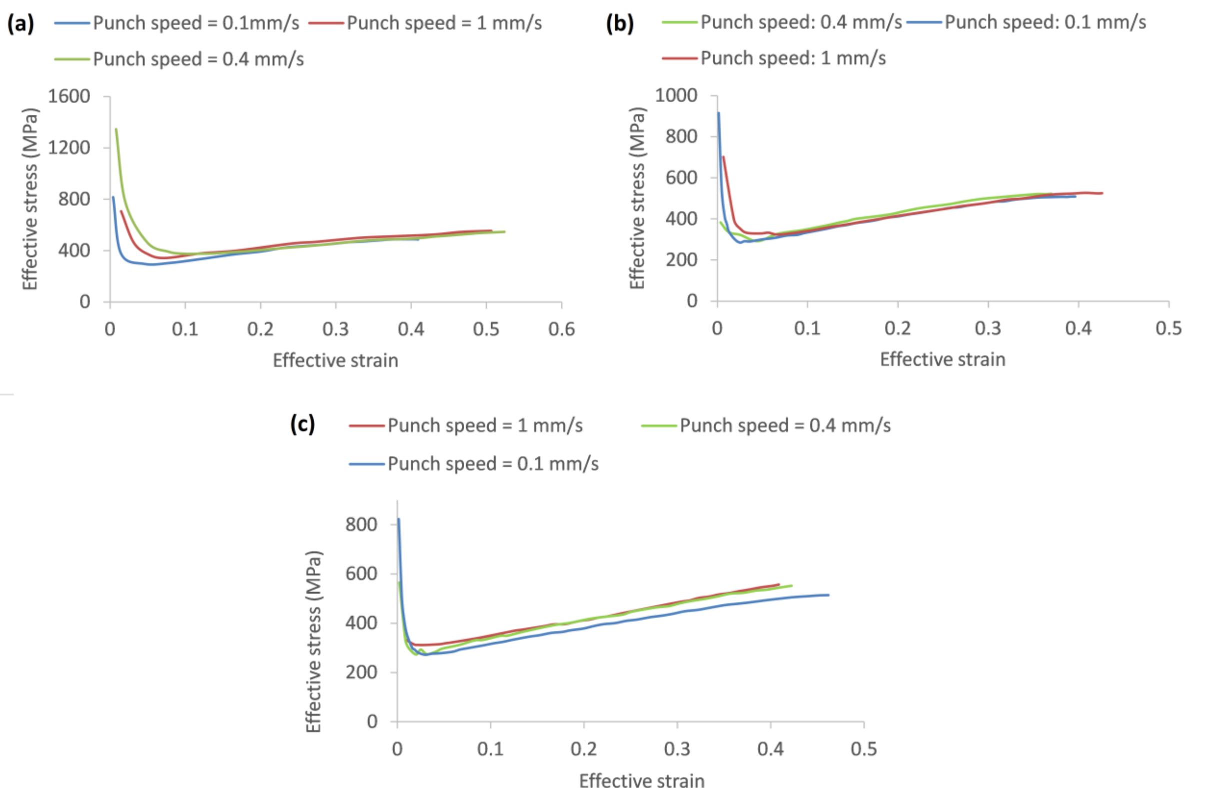

Figure 15. Stress-strain curves obtained at different punch speeds from the Erichsen experiments; a) the P_D = 8 mm, b) the P_D = 20 mm, c) the P_D = 25 mm

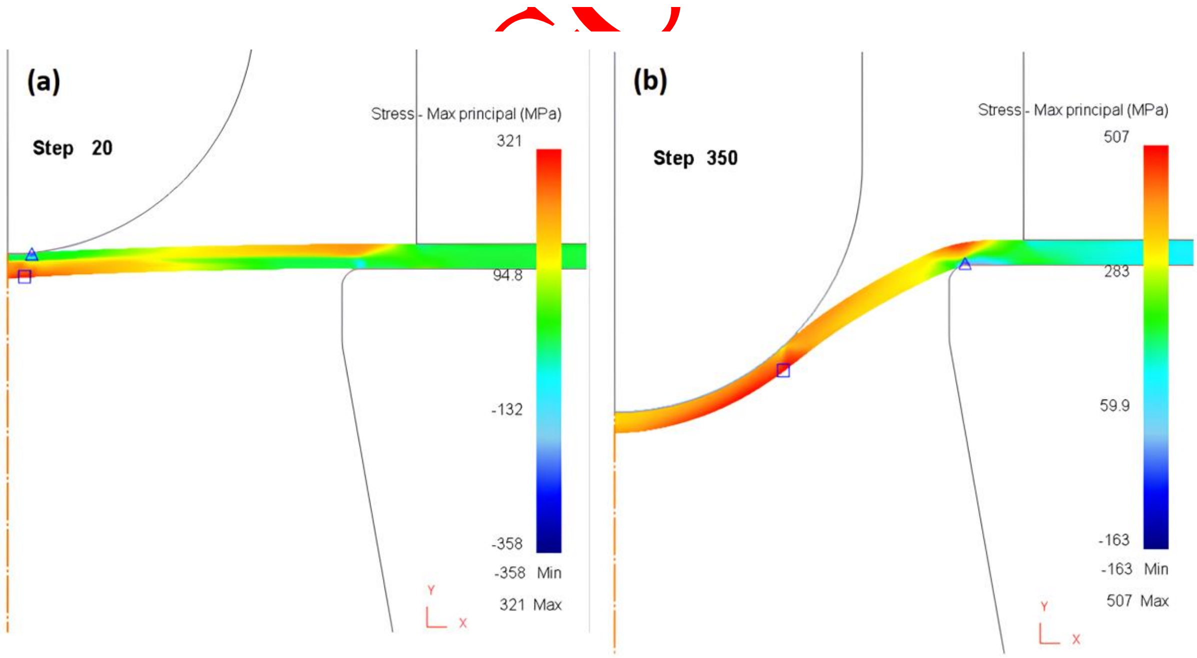

Figure 16. Principal stresses generated during the Erichsen test simulations: a) punch advancement = 0.4 mm, b) punch advancement = 7.0 mm

As shown in Equation 4, the Erichsen index increases linearly with the punch diameter. Figure 17 illustrates the variation of the Erichsen index with the punch diameters. When the punch diameter is 25 mm, the EI values are higher than expected. This is due to the larger die bore radius/punch radius ratio (R_D/R_P) in the experimental setup with the 25 mm punch compared to the other setups. The increase in this ratio reduces the β angle, which in turn results in a higher EI value.

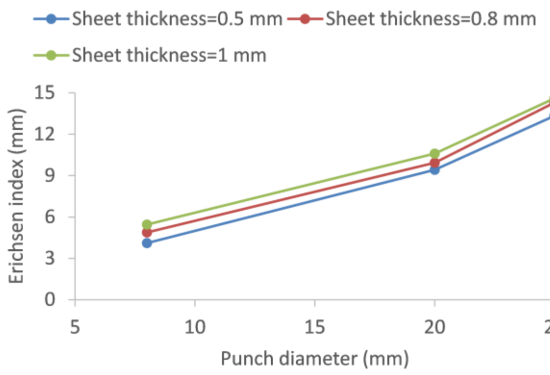

Figure 17. Variation of the Erichsen index with the punch diameters

The effective strain depends solely on the angles θ and β, as shown in Equation 9. Figure 18 demonstrates how effective strain changes with the angle θ. In the experimental setup with the 25 mm diameter punch, the R_D/R_P ratio is higher compared to the setups with the 8 mm and 20 mm diameter punches. As a result, greater effective strain values are obtained with the 25 mm diameter punch at the same θ angle.

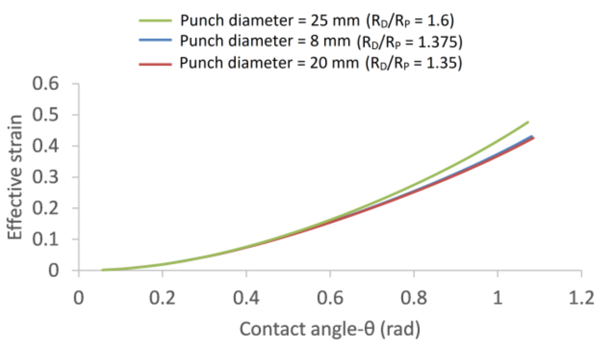

Figure 18. Variation of the effective strain ($\bar{\varepsilon}_\theta$) with the contact angle (θ)

Table 9 demonstrates that both the contact angle and fracture strain increase as sheet thickness increases. Kamikawa and Morino [22] attributed the increase in the Erichsen index with sheet thickness to Barba's law, which states that uniform elongation is independent of the cross-sectional area while post-necking (nonuniform) elongation increases in proportion to the square root of the cross-sectional area. However, this law was originally proposed for uniaxial tensile tests and is not sufficient to fully explain the variation in the Erichsen index with sheet thickness. For instance, Kocanda and Jasinski [7] observed that both uniform and nonuniform elongation increased by 14% and 13%, respectively, when the sheet thickness increased from 1 mm to 2 mm in the Erichsen tests on DC04 steel sheets. Table 9 indicates that fracture strains are higher when the punch radius is 4 mm compared to those obtained with the other punch radii for the same sheet thickness. Therefore, the impact of sheet thickness on the Erichsen index must be considered alongside the punch radius. Figure 19 illustrates that the influence of sheet thickness on the Erichsen index is more pronounced when the punch diameter is 8 mm. It was discovered that when the punch radius was 4 mm and the sheet thickness increased from 0.5 mm to 1 mm, the fracture strain and EI values rose by 68% and 32.8%, respectively. However, when the punch radius was 10 mm, increasing the sheet thickness from 0.5 mm to 1 mm led to a 31.2% rise in the fracture strain and a 12.5% increase in the EI value.

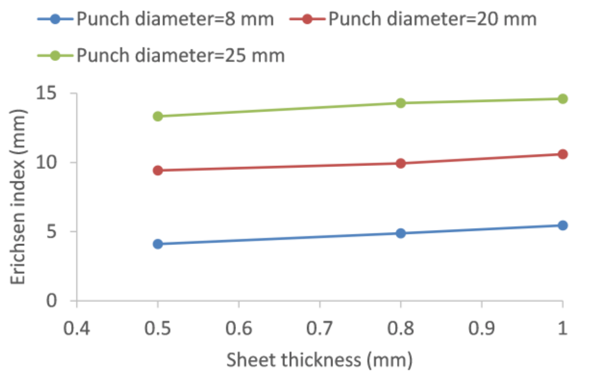

Figure 19. Variation of the Erichsen index with the sheet thicknesses

Table 9. Calculated contact angles and estimated fracture strains in the necking region

Experiment-No	Punch radius (mm)	Sheet thickness (mm)	Contact angle- θ (°)	Fracture strain for the frictionless condition	Predicted fracture strain
1	4	0.5	61.17	1.02	0.6936
2	10	0.5	58.14	0.916	0.623
3	12.5	0.5	57.48	0.945	0.6424
4	10	0.8	60.5	0.991	0.7234
5	12.5	0.8	60.44	1.046	0.7636
6	4	0.8	69.3	1.319	0.963
7	12.5	1	61.41	1.08	0.81
8	4	1	74.72	1.554	1.1655
9	10	1	63.48	1.09	0.8175

When comparing experiments with the same punch diameter, it is observed that increasing the sheet thickness to punch radius ratio (t_i/R_p) intensifies the bending effect, leading to higher fracture strains. This is thought to be due to the stress gradients created by the bending, which delay the onset of necking and allow for greater strains at fracture. Several studies in the literature suggest that bending effects and stress gradients can indeed delay necking. For instance, Fictorie et al. [31] noted that when a stress gradient develops across the thickness of the sheet, necking in the outer layer with higher deformation does not lead to plastic instability. Instead, the inner layers retard necking across the entire sheet, making the strain gradient less detrimental than uniform deformation. Additionally, Tharrett and Stoughton [32] stated that necking occurs when the strain on the concave surface exceeds the forming limit strain reached during in-plane deformation.

The punch force-displacement curves, generated from simulations using the predicted fracture strains (Table 9), are shown in Figure 20. It can be observed that the EI values derived from the simulation closely match the experimental results, with the Mean Absolute Percentage Error (MAPE) of 2%.

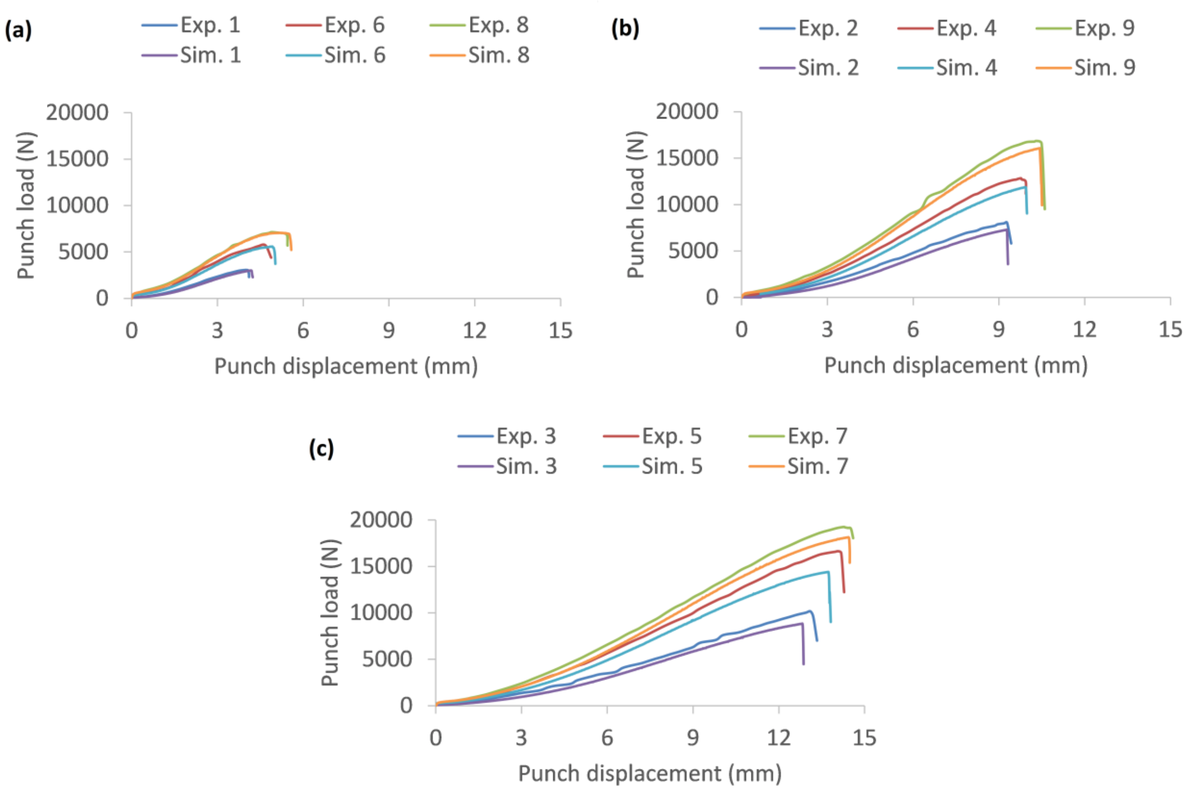

Figure 20. Displacement-punch force curves plotted using both experimental and simulation data of the DC04 steel sheets; a) the P_D = 8 mm, b) the P_D = 20 mm, c) the P_D = 25 mm

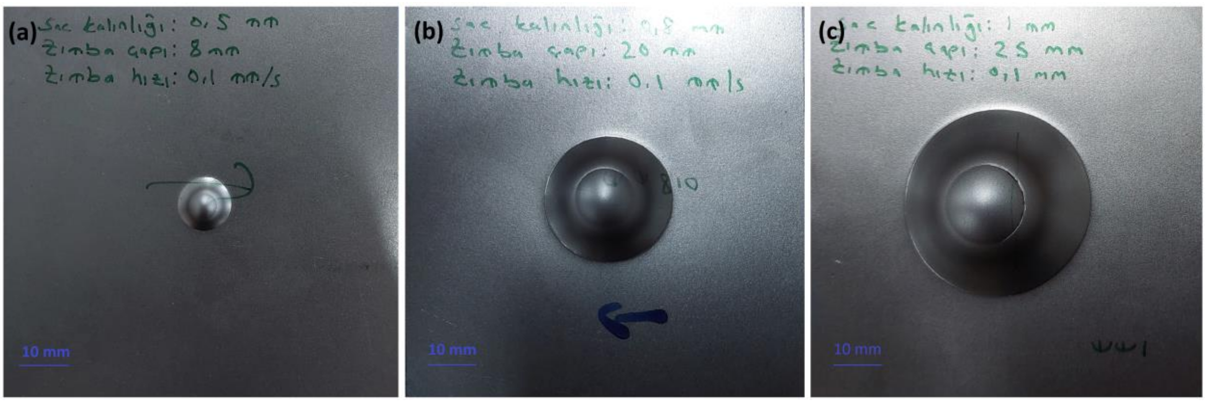

Figure 21. Deformations occurring after the Erichsen cupping tests on the DC04 steel sheet samples; a) the P_D = 8 mm, b) the P_D = 20 mm, c) the P_D = 25 mm

As shown in Figure 21, cracks in the DC04 steel sheets appeared in the annular regions, where local thinning (necking) occurred, for all of the experiments. It is evident that both the deformation region and the diameter of the annular crack zone increase as the punch diameter increases.

Figure 22 presents a schematic representation of the deformation and cracks that form in the sheet metal following the Erichsen test. In the frictionless case, the crack is expected to form at the pole of the deformed sheet during the Erichsen test [27]. Additionally, it has been stated that the radius of the annular crack zone expands with an increase in the friction coefficient [17].

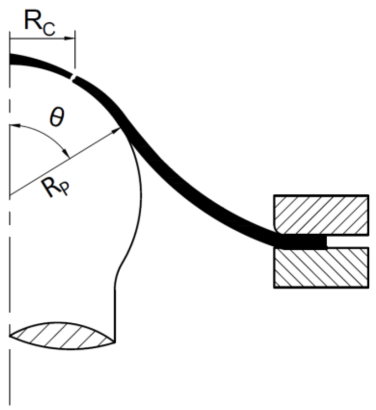

Figure 22. Schematic illustration of the crack formed during the Erichsen test.

The crack zone radius (R_C), determined through experiments and simulations, is provided in Table 10. The deformations occurring in the sheet metal during the Erichsen test were accurately predicted via simulations, with the resulting R_C values showing a 3.5% Mean Absolute Percentage Error (MAPE). Crack formation and the effective strains in the Erichsen simulations of the 1 mm thick DC04 steel sheet are presented in Figure 23. It was noticed that as the punch diameter increased, the bending effect diminished, resulting in a reduction of the effective strains reached before fracture.

Table 10. Radii of the annular crack zones after the experiments and simulations

Experiment-Simulation No	Punch radius (mm)	The radius of the annular crack zone (Experiment)	The radius of the annular crack zone (Simulation)
1	4	2.81	2.67
2	10	6.82	6.58
3	12.5	8.76	8.14
4	10	6.86	6.68
5	12.5	8.47	8.09
6	4	2.86	2.76
7	12.5	8.7	8.42
8	4	2.97	2.94
9	10	6.75	6.68

4. CONCLUSIONS

This paper examined the impact of punch diameter, sheet thickness, and punch speed on the Erichsen index and maximum punch load during the Erichsen tests on the DC04 steel sheets by utilizing both experimental and finite element methods. The findings are outlined below.

- The uniaxial tensile tests revealed that DC04 steel sheets exhibit excellent ductility, with a total elongation of 40% in the rolling direction.
- The punch force showed an almost linear increase with increasing punch diameter and sheet thickness. Increasing the punch speed also raised the punch force, but the effect was minimal.
- It was found that the EI increases linearly with the punch diameter, and the EI value also increases as the ratio of die bore radius to punch radius (R_D/R_P) increases.
- It was noticed that the effective strain is influenced only by the contact angle and the

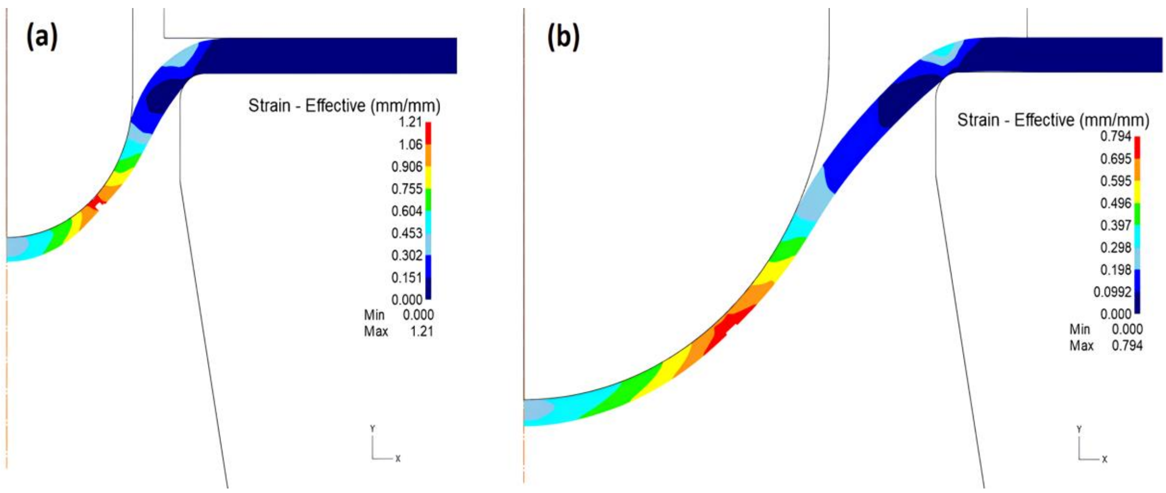

Figure 23. The effective strain values occurring in the DC04 steel sheet at the moment the crack initiates; a) the P_D = 8 mm, b) the P_D = 20 mm

R_D/R_P ratio, and the strain values increase with the increasing R_D/R_P ratio.

- It was observed that the Erichsen index and fracture strain values increase with rising sheet thickness. Additionally, the impact of sheet thickness on the EI and fracture strain values becomes more significant as the punch diameter decreases. For example, when the punch diameter was 8 mm, and the sheet thickness was raised from 0.5 mm to 1 mm, the Erichsen index (EI) increased by 32.8%. However, when the punch diameter was 20 mm, increasing the sheet thickness from 0.5 mm to 1 mm led to a 12.5% rise in the EI value.
- It has been monitored that the punch displacement-force curves and crack locations obtained from the simulations and experiments exhibited good congruence, and the MAPE does not exceed 3.5%.
- In automotive part manufacturing, optimizing sheet thickness and punch radius according to the results of this study could help minimize the risk of forming defects, such as excessive thinning or cracks. This would result in fewer defective parts, lower scrap rates, and a more cost-efficient manufacturing process.

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DECLARATION OF ETHICAL STANDARDS

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

AUTHORS'CONTRIBUTIONS

Fatih CİVELEK: Conducted the experiments, analyzed the results, and wrote the article.

Ahmet ÖZDEMİR: Performed the literature review and contributed to evaluating the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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