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EFFECT OF EQUAL CHANNEL ANGULAR PRESSING PROCESS ON DRAWABILITY OF DC04 STEEL SHEETS

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Abstract

Equal channel angular pressing (ECAP) is a severe plastic deformation (SPD) technique that induces substantial changes in the crystalline structure of materials, leading to enhanced mechanical properties. The aim of this experimental work is to study the influence of ECAP on the drawability of DC04 steel sheets. A multilayer sample of six sheets was deformed at room temperature with an internal channel angle of 120° in a single pass. The characterization was performed by measuring hardness and performing tensile tests, along with optical microscopy and X-ray diffraction (XRD) analysis. In addition, a finite element simulation was carried out with Abaqus. The Erichsen test was used to assess the drawability of the sheet with the best mechanical properties. The results showed a significant increase in microhardness, with an improvement of 64% compared to the original microhardness. Microstructural analysis showed a 70% reduction in grain size, with slight texture formation and no phase change. Tensile tests showed an increase in yield stress (Re) and ultimate tensile strength (Rm), accompanied by a decrease in elongation (A%) and strain hardening exponent (n). The Erichsen test demonstrated a slight 10% reduction in the Erichsen cupping index (IE). Overall, we succeeded in improving the mechanical properties of the DC04 steel plates while maintaining good drawability.

Keywords: *ECAP; Drawability; Erichsen test; DC04 steel sheets; Simulation; Manufacturing technologies*

1. Introduction

In the field of metal forming, deep drawing is used in the manufacturing industry for the production of various components such as automobile bodies, aircraft panels, domestic appliance bodies, kitchen utensils, and beverage cans [1]. The ability of a material to undergo deep drawing is influenced by its inherent properties, determined by its chemical composition and structure [2]. Advanced processing techniques can achieve changes in these properties. ECAP is defined as a method of severe plastic deformation (SPD). This method is an innovative one invented and explained by Segal and developed by Valiev [3] and Langdon [4], which details the principle of ECAP and the influence of different parameters.

The DC04 is a deep-drawing steel suitable for the high requirements of forming. It mainly has potential for light structural applications in the automotive and aerospace industries. This is due to properties such as reasonable strength and ductility [5, 6].

The scientific literature attests to a growing interest in the recent application of the ECAP process to improve the mechanical properties of materials. This improvement is achieved through the significant refinement of grain sizes, leading to the formation of ultrafine grains. Fukuda et al. [7] conducted a study on the influence of ECAP on cylindrical low-carbon steel billets with a section of 10 mm in diameter and a length of 60 mm. This study was carried out using route Bc in a canal with an interior angle (ϴ) of 90° and an exterior angle (Ψ) of 20°. The results demonstrated a reduction in grain size, leading to an increase in yield strength and ultimate tensile strength, accompanied by a decrease in elongation percentage. A. Chandra et al. [8] also worked with low carbon steel (0.2% by weight of C). The specimen used has a diameter of 12 mm and a length of 60 mm. ECAP process parameters were set at ϴ=120° and Ψ=20°, with a temperature range varying from 200 to 350 °C. A significant increase in Vickers hardness from 133 to 269 HV was observed, accompanied by a notable increase in tensile strength of about 2.2 times.

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However, the elongation decreased from 51% to 13%. M. Eddahbi et al. [9] examined the influence of (ECAP) on EUROFER 97 steel billets; EUROFER97 is the European Reduced Activation Ferritic-Martensitic (RAFM) steel, having dimensions of 12 mm × 12 mm × 65 mm. The ECAP was carried out at a temperature of 550 °C with an angle of 105° following route C. The conclusions of this study indicate an improvement in the mechanical behavior of this steel. This improvement is attributed to the grain refinement and texture evolution of the lamellar substructure induced by ECAP deformation, M. B. Jabłońska et al. [10] examined the effect of the Dual Roll Equal Channel Extrusion (DRECE) method on IF steel strips measuring 800 mm in length, 60 mm in width, and 2 mm in thickness. Their study demonstrated that after four DRECE passes, the fraction of low-angle grain boundaries (LAGBs) significantly increased from 7% in the initial sample to 54%. With an increase in the number of passes, the mechanical properties improved, with the yield strength reaching a maximum of 328 MPa after seven DRECE passes. However, the elongation to failure decreased significantly, from 46% in the as-received condition to 13% after seven DRECE passes, K. Kowalczyk et al. [11] focused on the effect of DRECE method on DC01 steel with dimension of 800 x 60 x 2 mm, after multiple DRECE passes, there is a marked increase in the formation of low-angle subgrain boundaries, reaching 51% after seven passes, indicating advanced microstructural transformation towards high-angle boundaries, Additionally, microhardness measurements reveal a significant increase in hardness with each pass, indicating material hardening and improved homogeneity.

On the other hand, the influence of ECAP on the drawability of low carbon steel DC04 has not yet been studied. Existing literature, such as the work of J. Suh et al. [12] on the impact of different ECAP routes (A, C, and D) on the texture and cold formability of AZ31 sheets, H.R. Rahimi et al. [13] on Al-Mg alloy plate (5083) using the ECAR process, and M. Ciemiorek et al. [14] on commercial alloy 3003 plates using Incremental ECAP, primarily focus on different materials and process modifications. These studies, while valuable, highlight the need for further research specific to low carbon steel DC04.

2. Material and methods

In this study, experimental trials were undertaken using an ECAP die. This die was designed at the Metal Materials Forming Laboratory (LMF2M) at Badji Mokhtar Annaba University to assess the impact of this technique on the mechanical properties and drawability of DC04 steel sheets. This investigation took place in two distinct phases. Initially, attention was paid to the influence of ECAP on the microstructure and mechanical properties of DC04 steel sheets. Subsequently, a study of drawability was conducted specifically on the sheet with optimal properties using the Erichsen test. These results contribute to understanding the effect of ECAP on the mechanical performance and drawability of DC04 steel sheets, offering perspectives for its application in forming processes.

2.1. Material

The material used in this study is low carbon steel DC04, developed at the SIDER El-Hadjar steel complex in Annaba. The latter is supplied in the form of cold rolled 1.5 mm thick sheets that are then annealed. Its chemical composition, obtained by spectroscopy, is recorded in Table 1.

Table 1. *Chemical composition of DC04*

Elements	C	Mn	Cu	Al	Ni	Cr
wt%	0.06	0.19	0.04	0.081	0.01	0.01

2.2. Methodology and experimentation:

Figure 1 shows the ECAP die used in our study. The die consists of a central part and an auxiliary part machined from 55NCDV7 steel, quenched in oil, followed by tempering. The assembly of these two parts forms two channels with the same cross section of 10x120 mm, namely the inlet channel and the other outlet. These two channels are connected by an elbow having an interior angle ϴ of 120° and an exterior angle Ψ of 10°, For the selection of the interior and exterior angles, we based our choice on the literature, where several studies have used these angles (120° and 10°). However, we are willing to use other angles [8, 14, 16] . Figure 2 shows samples before and after ECAP.

Figure 3a illustrates the principle of the ECAP technique used. Six sheets of dimension 119.9x100 mm were previously cut and then placed in multilayered sample in the die, as shown in Figure 1c. A punch with a rectangular section of 9.8x119.8 mm and a height of 100mm is used to extrude the sheets in the input channel, thus passing them through the elbow connecting the two channels. Figure 3b shows the orientation of rolling direction (RD) versus metal flow in ECAP.

In order to reduce friction, a molybdenum disulfide-based lubricant (MoS_2) was applied to the entire channel and between the sheets. The (ECAP)

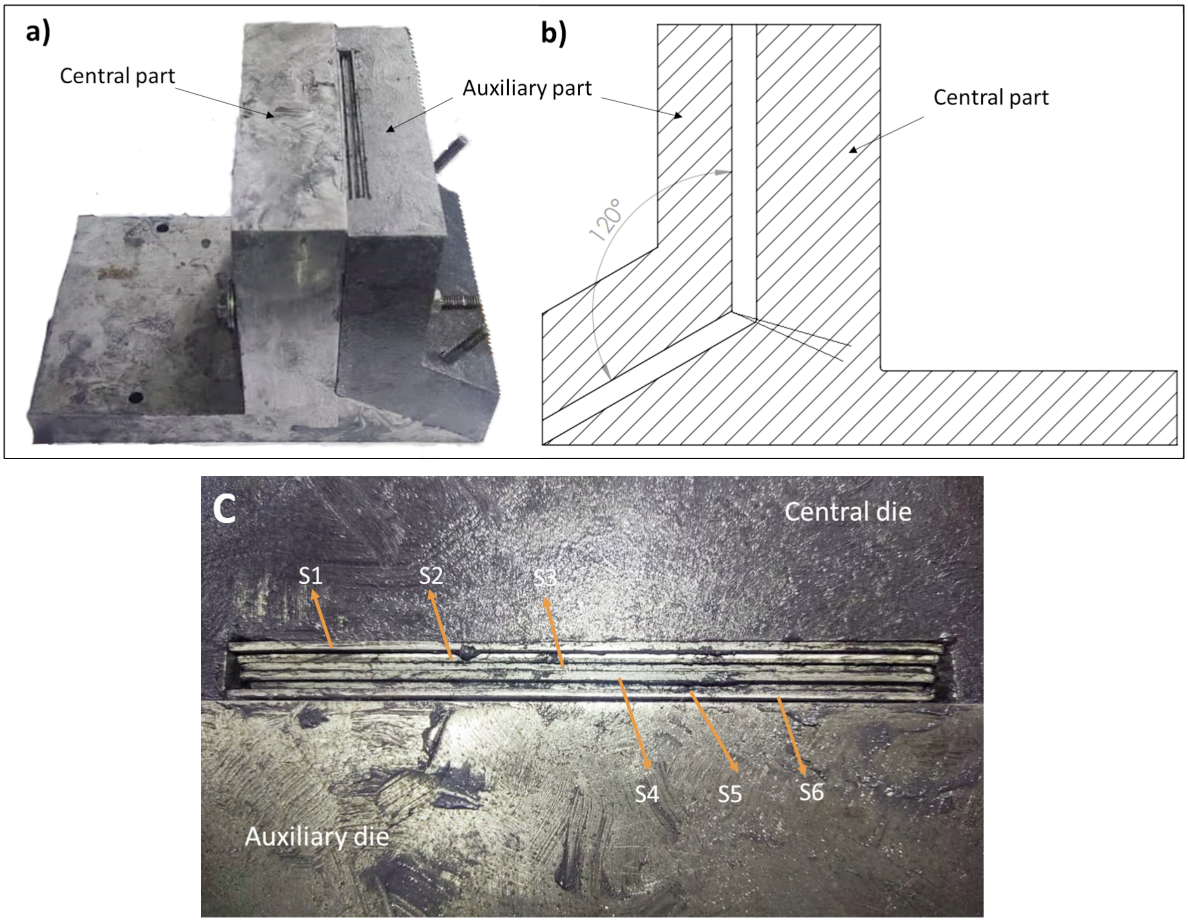


Figure 1. *a) ECAP die; b) ECAP die cross-section; c) Positioning of sheets inside channel*

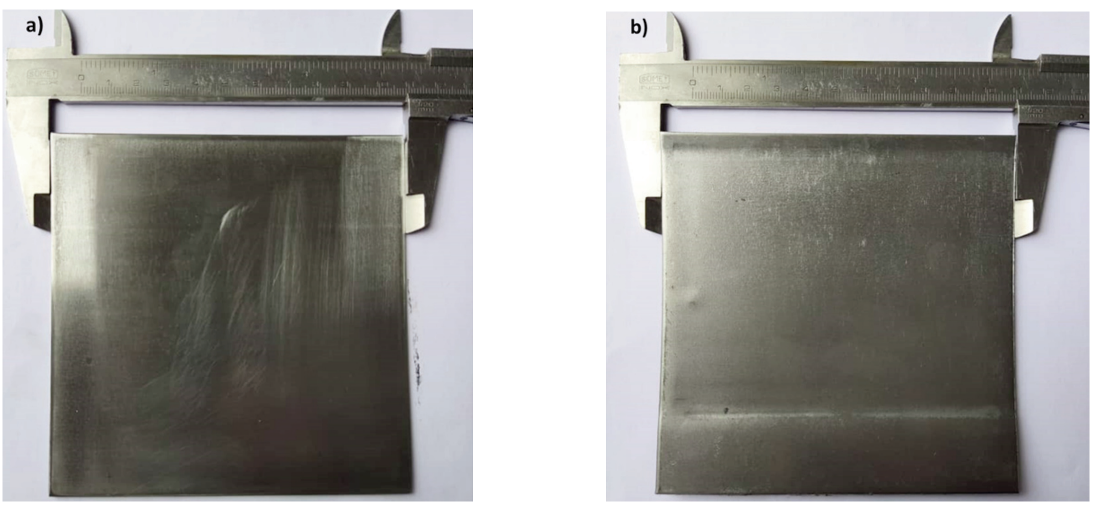


Figure 2. *DC04 steel sheet a) before ECAP, b) S1 after ECAP*

process was performed for a single pass with an internal angle of 120° and a pressing speed maintained at 0.5 mm/s. Microhardness measurements were carried out using a ZWICK brand Vickers durometer, applying a load of 200 gf. A total of seventeen measurements were taken for each sheet, and their average was noted. The configuration of the measurement locations is shown in Figure 4.

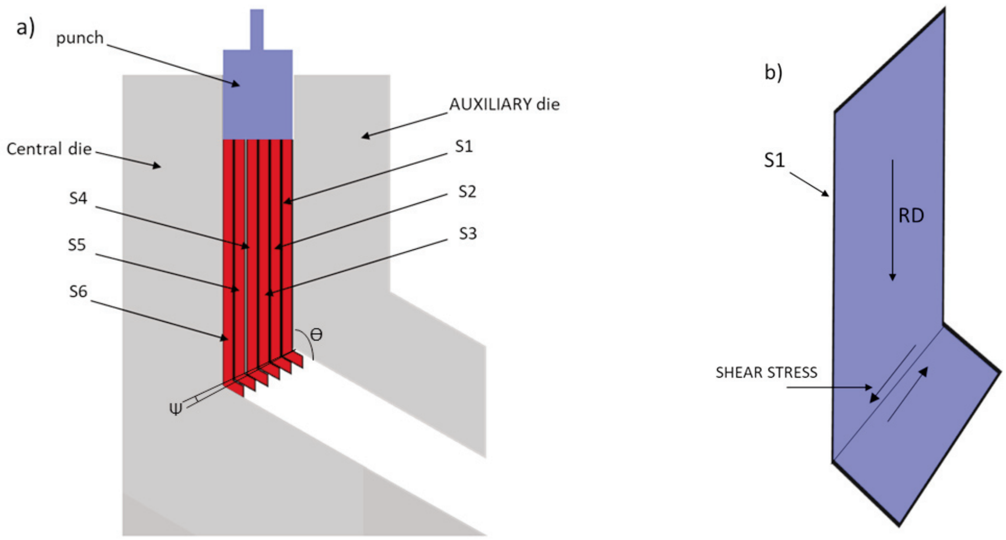


Figure 3. *a) schematic diagram of the ECAP process. b) rolling direction (RD) versus metal flow in ECAP*

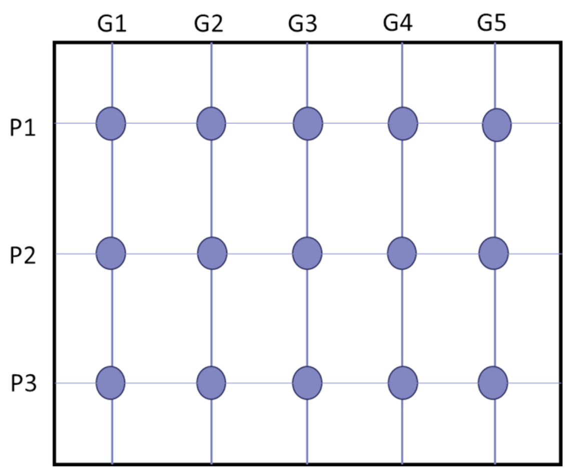


Figure 4. *Representation of the location of the 15 microhardness measurements*

2.3. Characterization of the microstructure

After sequential mechanical polishing using SiC abrasive paper from 400 to 4000 grit, a 2% Nital solution was used as an etching agent to reveal the grain structure. Optical microscopy was used to observe the microstructure of the sheets before and after ECAP.

X-ray diffraction (XRD) measurements were carried out on the surface of the sheets before and after ECAP, with the aim of evaluating possible structural changes and analyzing any changes in the diffraction peaks. The D8 ADVANCE BRUKER diffractometer was used with Cu-Kα radiation (λ = 1.54 Å) and a pitch of 0.02°.

2.4. Tensile test

To evaluate the mechanical properties of the sheets before and after the ECAP process, tensile tests were conducted using a ZWICK Z020 machine. The specimens were cut in the extrusion direction and dimensioned according to EN ISO 6892-1, as shown in Figure 5.

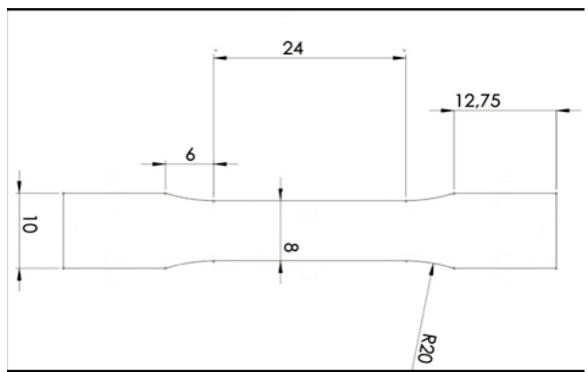


Figure 5. *Tensile test specimen according to EN ISO 6892-1*

2.5. Erichsen cup test

In order to assess the ductility and drawability of the sheets before and after ECAP, the Erichsen test was used in accordance with the standards DIN EN 10139 and DIN EN 10130.

The sheet to be stamped is fixed in a special hydraulic press, and a progressively increasing load is applied to the surface of the sheet by a hemispherical punch of 20mm diameter until a crack appears [17, 18]. Figure 6 schematically illustrates the Erichsen test.

The resulting deformation is measured in depth using a caliper and expressed in millimeters. The Erichsen index (IE) is calculated using the formula (Eq. (1)). A high Erichsen index (IE) indicates better ductility and drawability of the material.

$$IE = \text{depth of the cup} - \text{thickness of the sheet} \qquad (1)$$

The propagation and shape of the crack are also evaluated [19].

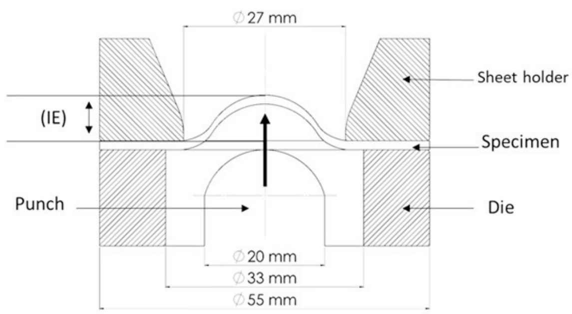


Figure 6. *Schematic diagram of the Erichsen cup test*

3. Results and discussions

3.1. Effect of ECAP on microhardness

The microhardness measurements, recorded in Figure 7, show an increase in microhardness for all of the sheets after ECAP, thus highlighting the beneficial effect of ECAP. This increase can be attributed to grain refinement [10, 19]. Position S1, which is in direct contact with the interior angle ϴ of the die, exhibits the most significant increase, with a value of 64%. This result can be explained by the greater deformation of the sheet S1, which is in direct contact with the wall of the die. The other sheets show a moderate increase of around 13%. Also, all the sheets after ECAP show a reduction in the standard deviation, thus suggesting a homogenization of the microstructure [10, 19].

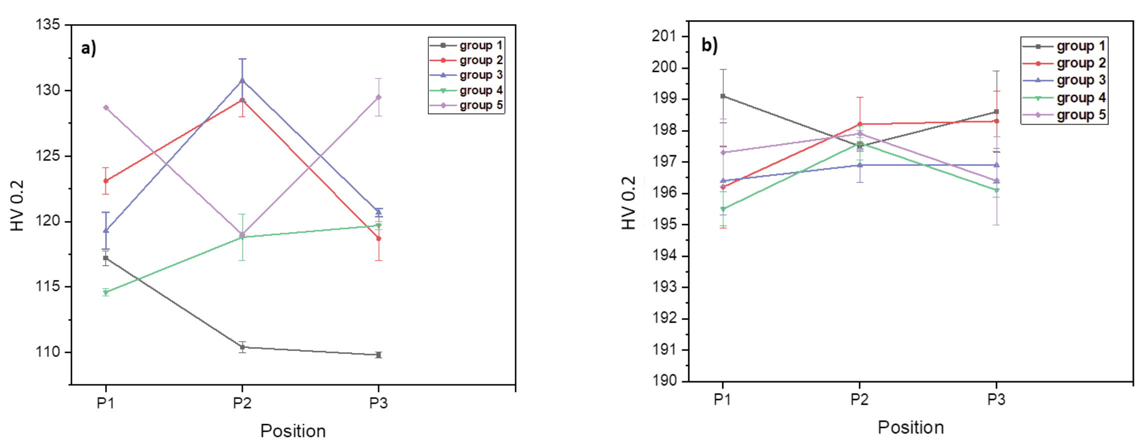
3.2. Simulation of the ECAP process

A finite element simulation was conducted with Abaqus software to provide a better understanding of the (ECAP) process.

The simulation is employed to provide direct insights into the evolution of plastic deformation during the ECAP of multilayered DC04 steel sheets. The effective deformation in ECAP is governed by the internal and external die angles, as described by the following criterion [21]:

$$\varepsilon = \frac{2}{\sqrt{3}}\left[2\cot\left(\frac{\theta}{2}+\frac{\varphi}{2}\right)+\varphi\, cosec\left(\frac{\theta}{2}+\frac{\varphi}{2}\right)\right] \qquad (2)$$

Consequently, plunger speed has minimal influence on the deformation process. However, a low speed is used to achieve better deformation uniformity. Slower speeds promote more homogeneous deformation across the material [22], though they require longer processing times. For our purpose, the real dimensions of the different parts and the experimental conditions were respected. The parameters of mechanical properties of the material were derived from experimental data, the strain hardening is introduced using by the hollomon model $\sigma = k\varepsilon^n$ and the material is considered isotropic. Since the plunger and die had no deformation and had no effect on the specimen's stress state, they were taken as rigid bodies, defined as solid discrete rigid with a mesh size of 10 mm (R3D4 type: A 4-node 3-D bilinear rigid quadrilateral); the sheets are considered as deformable solid extrusion elements, with a fine mesh size of 1 mm (C3D8R type: An 8-node linear brick, reduced integration, hourglass control). The friction coefficient 0.1 following the standard Coulomb's friction law was introduced and applied between all parts of the simulation (tool/sheet contact, sheet/sheet contact and tool/tool contact), this value is literature based on the work of Alateya et al. [23], this



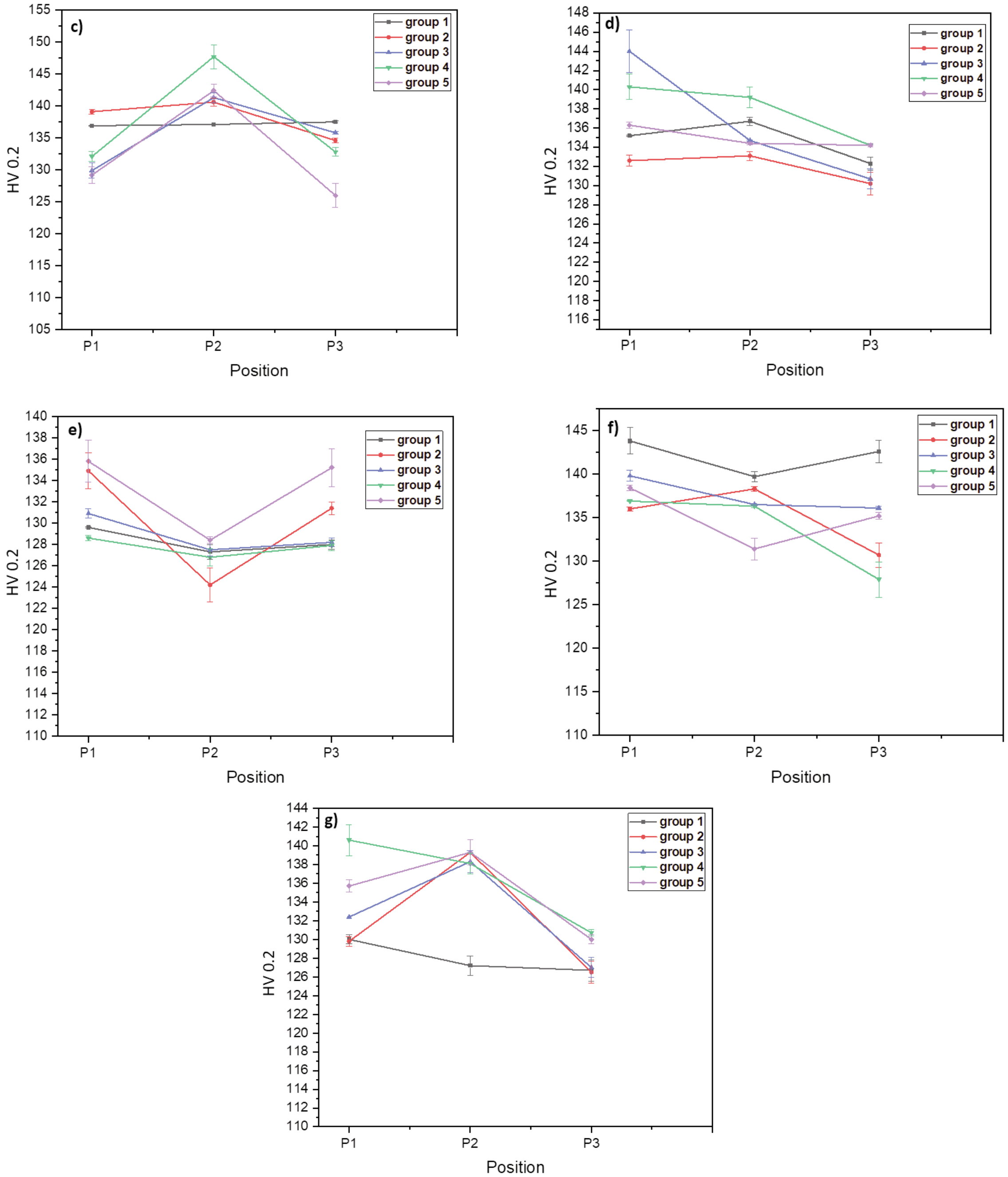


Figure 7. *Microhardness and standard deviation of HV 0.2: a) before ECAP, b) S1 after ECAP, c) S2 after ECAP, d) S3 after ECAP, e) S4 after ECAP, f) S5 after ECAP, g) S6 after ECAP*

is due to the use of lubrification during the process. The displacement of the plunger is 115 mm. Figure 8 illustrates the multilayered sample moving through the channel, providing a representation of the ECAP process from start to finish, including the Von Mises stress results of the experimental procedure.

Figure 9 shows in detail the stress distribution in the channel bend during ECAP process. Figure 9 clearly illustrates that stresses are concentrated mainly in the sheet in contact with the inside angle, while the other sheets are less affected. This observation explains the variation in micro-hardness values between S1 and the rest of the plates, highlighting that the most significant deformations are produced in plate S1. This stress concentration is also consistent with the behaviors observed in the ECAP of other bulk materials [19, 21, 24].

In accordance with the conclusions drawn from

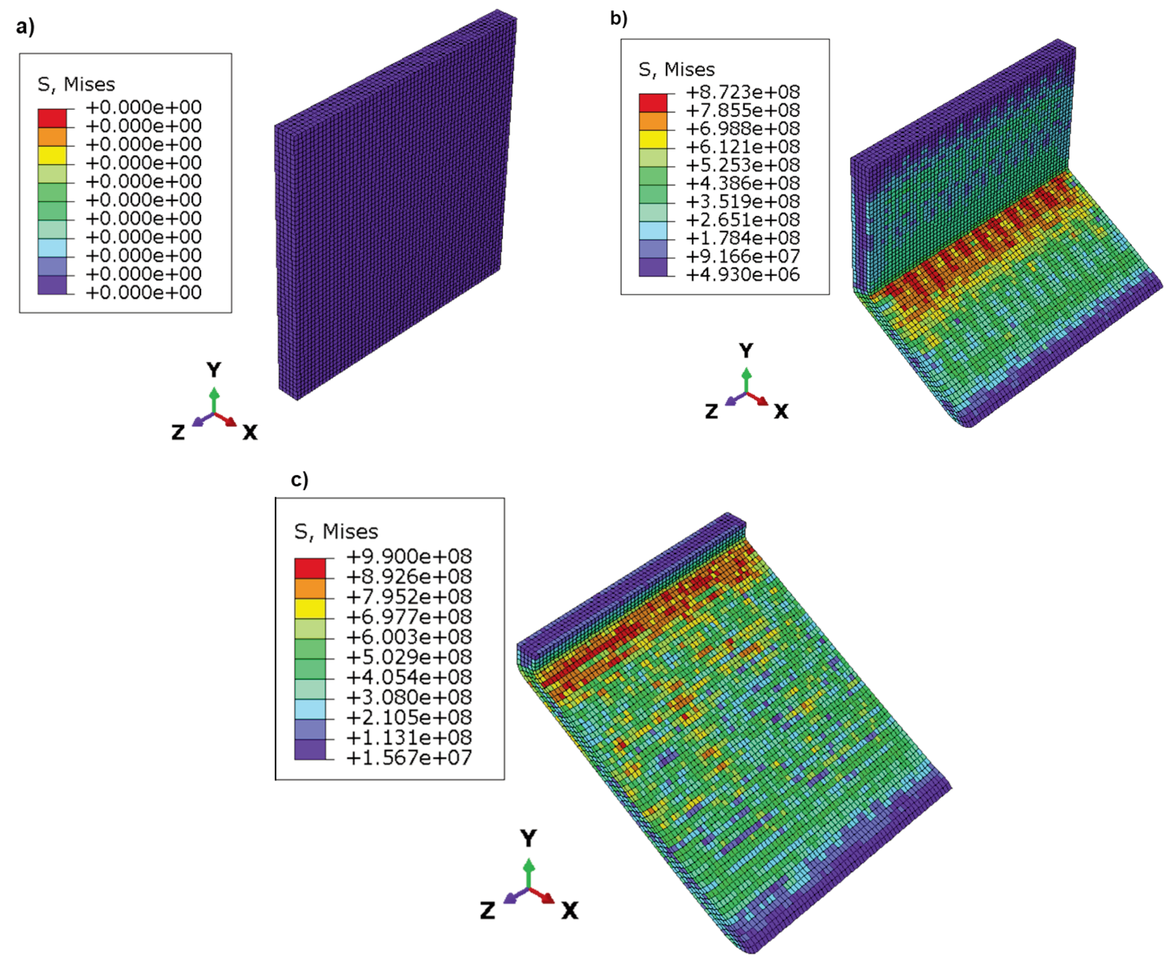


Figure 8. *ECAP simulation of DC04 sheets: a) initial state, b) middle of the simulation, c) end of the simulation*

the microhardness results and the simulation, it seems more appropriate to concentrate our analysis exclusively on the first sheet (S1), in order to deepen our understanding of the phenomenon.

3.3. Effect of ECAP on microstructure

Figure 10 shows the microstructure before and after ECAP of sheet S1, the specimens were taken from the center of the sheet represented by the location G3P2 in Fig. 4. Significant grain refinement was observed using optical microscopy, accompanied by a high density of grain boundaries (Fig. 10b). This phenomenon has also been reported by Fukuda et al. [7], M. Eddahbi et al. [9], and L. Wang et al. [26]. These optical micrographs highlighted deformation bands, indicative of the severe plastic deformation inherent to the ECAP method [10]. Additionally, the alignment of elongated grains along the shear direction suggested the development of a specific texture [27]. This grain refinement can be attributed to the severe plastic deformation generated during the pressing process through the channel, where the ferrite undergoes successive subdivision of the dislocation walls, facilitated by the operation of multi-slip systems [15, 26, 28, 29]. The transformation from an initial coarse grain structure to a finer, more homogeneous grain distribution after ECAP is clearly demonstrated in the optical micrographs.

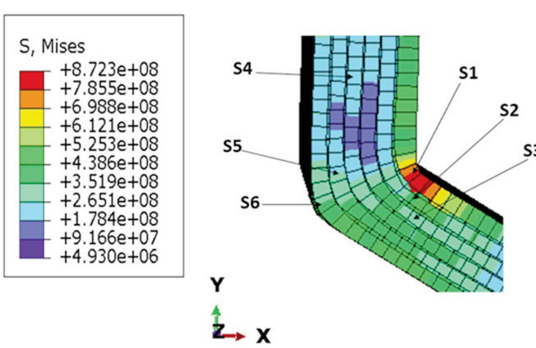


Figure 9. *Distribution of stress of V. Mises during the simulation*

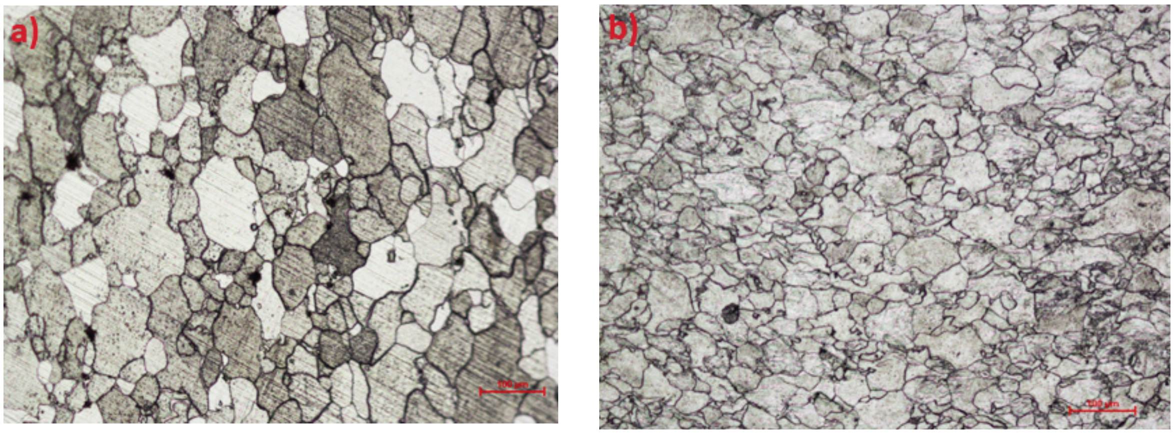


Figure 10. *Microstructure of the sheet (x100): a) before ECAP; b) S1 after ECAP*

Grain size was assessed using the intercept method, with cross and circle marks, before and after ECAP. Figure 11 illustrates the method, and the results are summarized in Table 2.

Table 3 shows a decrease of approximately 70% in the length of intersection between grain boundaries after ECAP. This finding supports the observation that grain size decreases after ECAP (Fig. 10).

Figure 12 illustrates the distribution of intersection lengths in the intercept method, before and after ECAP. Before ECAP (Fig. 12a), the distribution extends up to 600 µm, where 70% of the intersection length is concentrated between 0 and 150 µm. After ECAP (Fig. 12b), a reduction in the distribution range appears and now extends up to 120 µm, where 80% of the intersection length is concentrated between 10 and 60 µm. Thus, the homogenization of the grains size after ECAP is confirmed [9, 30].

3.4. X-ray diffraction (XRD) analysis

Figure 13a illustrates the X-ray diffraction (XRD) diagrams of the sheet before and after ECAP. The two diagrams show three distinct peaks at angles (2θ) of 44.9°, 65.2°, and 82.5°, attributed respectively to the crystalline planes (110), (200), and (211) of the Im-3met space group associated with the centered cubic crystalline structure (phase α), indicating that the ECAP did not cause any phase change in DC04 steel plate.

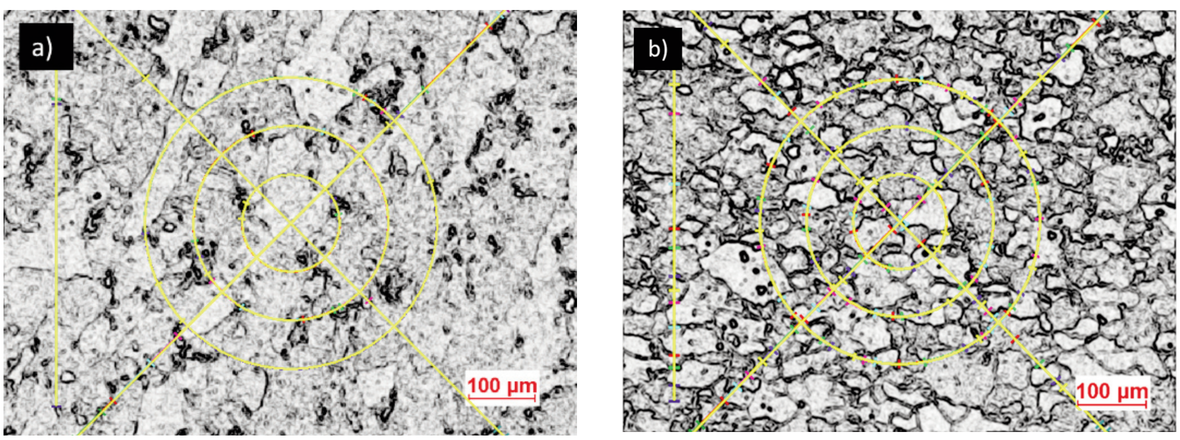


Figure 11. *Intercept method (x100): a) before ECAP; b) S1 after ECAP*

Table 2. *Length of the intersection between grain boundaries and the average linear intercept in the intercept method*

Length of intersection between grain boundaries (µm)			average linear intercept (µm)	
	Before ECAP	S1 After ECAP	Before ECAP	S1 After ECAP
Minimum	6.8	8.2	132.11	38.56
Maximum	591.7	114.1		
Mean	132.1	38.6		

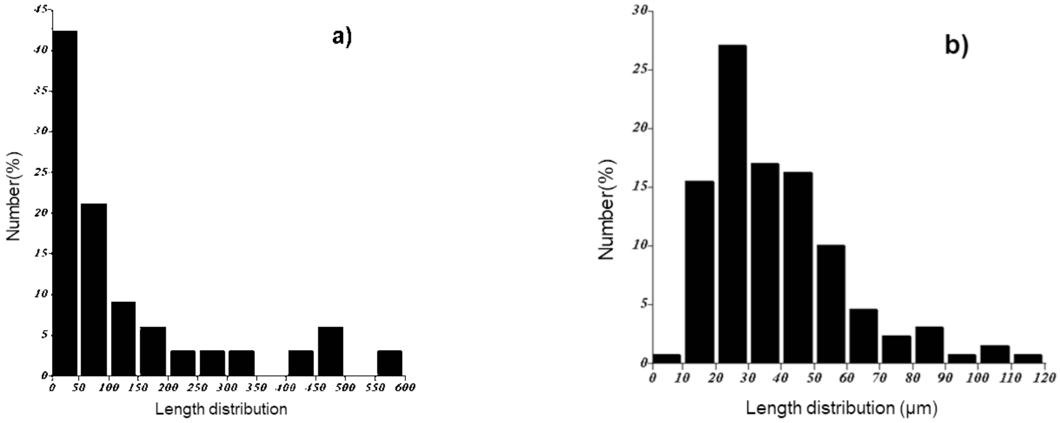


Figure 12. *Length distribution: a) Before ECAP, b) S1 after ECAP*

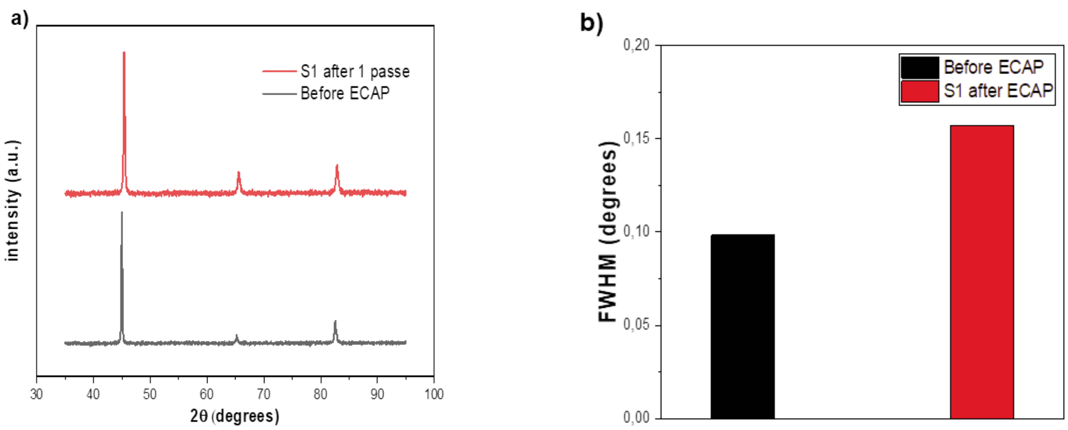


Figure 13. *a) X-ray diffraction patterns before and after ECAP; b) FWHM values*

Figure 13b shows the measured full width at half maximum (FWHM) values of the main peaks (2θ equal to 44.9°). Compared to the sample before ECAP, the FWHM of the peak after ECAP is significantly higher, indicating that the treatment caused a decrease in grain size [10, 31]. This corroborates the conclusions about the decrease in grain size after ECAP, previously made.

3.5. Effect of ECAP on mechanical properties

Figure 14 presents the tensile graphs of the samples before and after the ECAP. The results of the tensile tests are noted in Table 3.

Table 4 shows an increase in yield strength (Re) and maximum strength (Rm) of 20% and 8.3%, respectively. Furthermore, a reduction of 27%, 10.17%, and 52.17% were noted in elongation (A%), the strain hardening coefficient (K), and the work hardening coefficient (n), respectively was noted. Similar behaviors have been reported in the literature [13, 22, 32]. These changes can result from several factors, such as the decrease in grain size and the increase in dislocation density [34].

3.6. Effect of ECAP on drawability

Figure 15 shows the method of measuring the deformation depth of samples after Erichsen testing using a caliper. Figure 16 shows the crack in the plates after the Erichsen test. Table 4 presents the results of the Erichsen test.

After ECAP, a 10.2% decrease in the IE parameter was noted. This reduction is consistent with the results of the tensile tests carried out. Despite this reduction, it should be noted that the sheets have retained a good suitability for stamping. Figure 16 further supports this point, revealing the presence of concentric cracks in the sheets not subjected to ECAP, and subjected to ECAP. This observation serves as a secondary indicator confirming the suitability of the material for deep drawing processes after ECAP [25]. It can be noted that the tensile test revealed a work hardening coefficient (n) reduced by more than 50% after ECAP. However, the sheet maintained a good drawability. Consequently, the work hardening coefficient does not seem to be a reliable indicator of the drawability of the sheet.

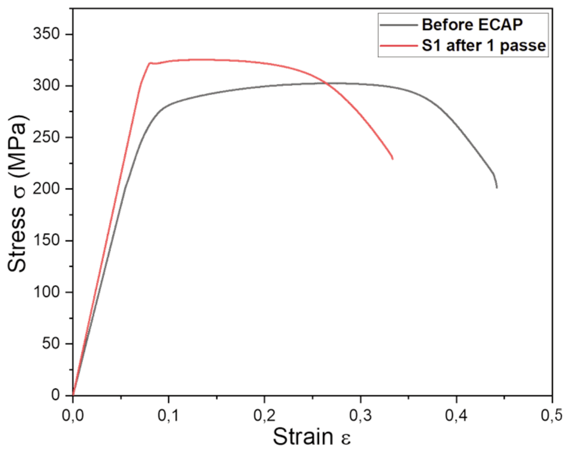


Figure 14. *Strain-stress curves before and after ECAP for S1*

by the Erichsen test [10]. The difference arises because tensile tests measure uniaxial stress, whereas deep drawing involves complex multi-axial stresses that exploit the weaknesses introduced by grain elongation. Furthermore, while ECAP significantly refines the grain structure, leading to enhanced strength, it often results in a decrease in ductility. This reduction can be attributed to several factors: grain elongation, high dislocation density, and the presence of non-equilibrium grain boundaries [26, 28, 29]. These factors collectively reduce the material's ability to accommodate further plastic deformation.

3.7. Surfaces and sub-surfaces after Erichsen testing

Figure 17 shows an overview of the different

Table 3. *Difference in mechanical proprieties before and after ECAP for Sheet 1*

Proprieties	Re /MPa	Rm /MPa	A%	n	K
Before ECAP	267	300	37	0.23	532.8
S1 after ECAP	320	325	27	0.12	478.6

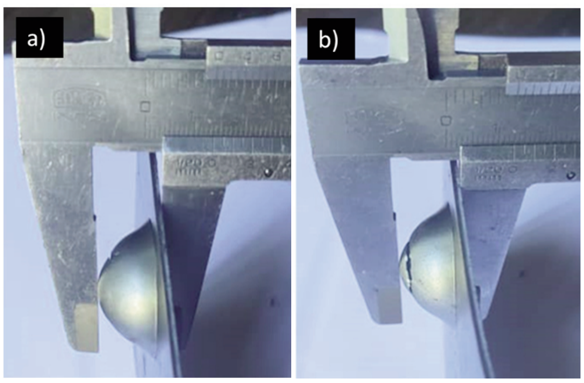


Figure 15. *Method of measuring the deformation depth of the cup: a) before ECAP; b) after ECAP*

The reduction in the Erichsen Index (IE) can be attributed to the elongation of grains observed through optical microscopy. These elongated grain boundaries act as preferential sites for the initiation and propagation of cracks during deep drawing processes, leading to a decrease in formability [35]. This finding contradicts tensile test results, which often show improved strength and ductility due to grain refinement. Saray et al. [36] observed similar outcomes in their study on the formability of Interstitial-Free (IF) steels, where severe plastic deformation (SPD) techniques like ECAP enhanced tensile properties but reduced formability as measured

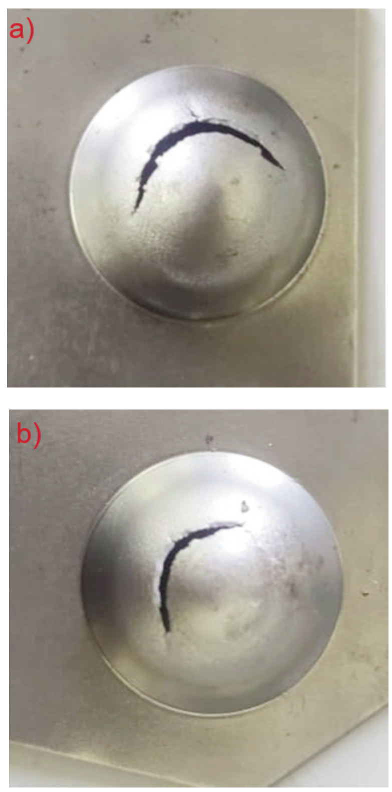


Figure 16. *Plate cracking after Erichsen test: a) before ECAP; b) after ECAP*

Table 4. *Erichsen test results*

	Initial steel sheet thickness /mm	Depth of the cup/mm	average IE /mm	Load /KN
Before ECAP	1.5	13.3	11.8	12.3
S1 after ECAP	1.5	12.1	10.6	14.2

deformation zones that the sheets underwent after the Erichsen tests. It is observed that the deep drawing process generated the formation of three clearly demarcated zones, designated respectively as zone A, zone B, and zone C, each exhibiting a distinct surface morphology. We see that the surface morphologies are the same for the two samples; these areas are shown in fig. 17a and fig. 17b. Zone A is formed under the effect of friction forces between the punch and the sheet metal, it has a rather smooth surface. Zone B is stretched under the influence of biaxial tensile loads; it presents the roughest surface due to the concentration of deformation bands. Zone C is deformed with biaxial bending loads, it presents a smooth surface, which indicates that this zone does not undergo considerable plastic deformation. These results are explained more deeply by Saray et al. [36].

3.8. Simulation of the Erichsen tests

The numerical simulation of the Erichsen tests was carried out using Abaqus software to study the concentration of strains during these tests, before and after ECAP. In this simulation model, the die, the blank holder, and the punch are considered rigid elements and modeled as discrete rigid solid elements, the sheets are modeled as isotropic deformable element and modeled in solid deformable shell. The mesh of rigid parts (tools) is defined by the R3D4 type, while the blank is defined by S4R. The displacement of the punch into the die is 40 mm. The choice of the blank holder force and the choice of the friction coefficient has been the subject of several studies that give a balance between them [37]. For our work, the blank-holder force applied is 1.3 kN, which is measured by the Ericksen test machine. The coefficient of friction between the tools and the sheet is assumed to be 0.15 considering the dimension used. This simulation of the Erichsen test and the concentration of strains are shown in Figure 18. Similar strain concentration was observed in the two sheets; the highest strains are located in zone B, which corresponds to the breaking point of the sheets. This result is the same as that obtained for the experimental tests in Figure 17. Lower strains were recorded in zone A, and negligible strains were recorded in zone C.

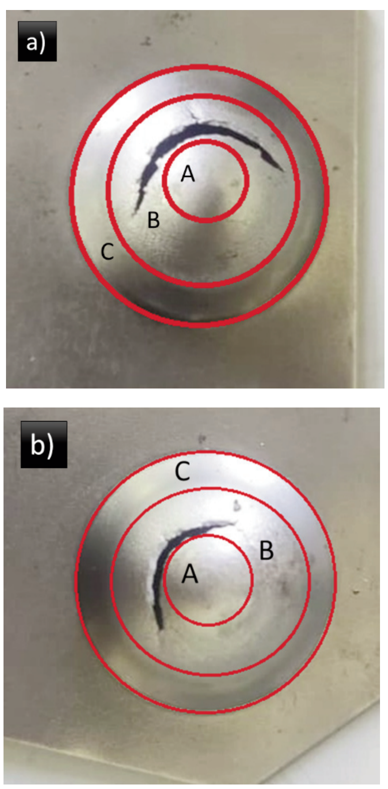


***Figure 17.** Different deformation zones that the sheets underwent after the Erichsen tests: a) before ECAP, b) S1 after ECAP*

The true strain/thickness graph was plotted for both scenarios, focusing on the node exhibiting the highest strain in each simulation. The plot is shown in Figure 19. It was observed that the deformation of S1 after ECAP initiated later than that of the as-received sheet, as evidenced by the initial reduction in thickness. However, Sheet 1 reached a thickness of 0 mm at a lower strain, indicating the onset of cracking. These simulation results align with experimental findings, which demonstrate a reduction in the Erichsen Index (IE) factor during the Erichsen test.

3.9. Load-displacement curves during the Erichsen tests

Figure 20 illustrates the load-displacement curve of the punch during stamping for the two sheets (before and after ECAP for S1) as obtained from the simulation. We observe that the maximum punch load required to deform Sheet 1 after ECAP (14.103 kN) is greater than that required to deform the sheet before ECAP (12.103 kN), with the maximum load indicated by point a. This increase is attributed to the homogenization of the structure due to grain refinement (discussed in section 3.3) and the increase in microhardness (shown in section 3.1) after ECAP. These findings are also supported by Ciemiorek et al. [20]. Beyond this point, there is a reduction in the punch load, which results from the initiation and propagation of cracking. The reduction in load provides insights into the nature of sheet failure during deep drawing [38]. For sheet S1 after ECAP, analysis begins at point b, which represents the actual point of crack initiation, as evidenced by the

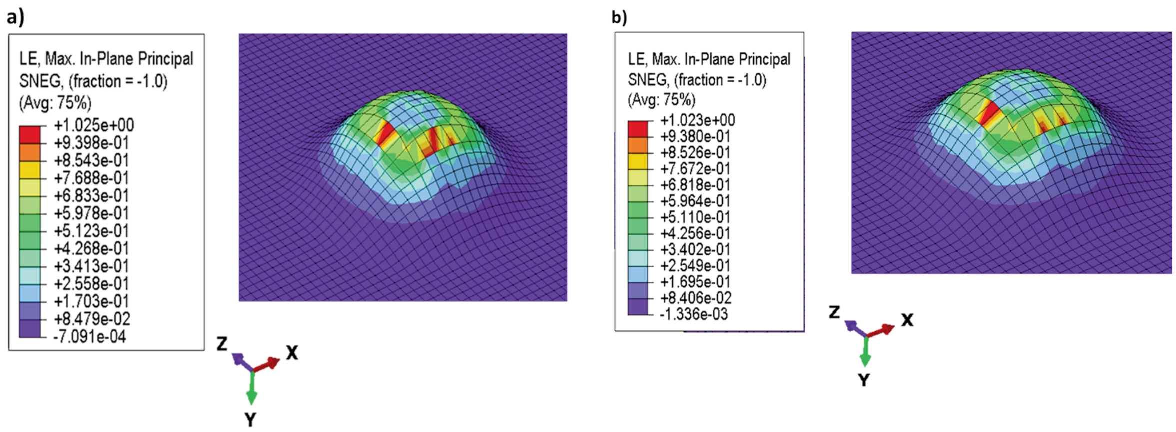


Figure 18. *Simulation of the Erichsen tests of sheets: a) before ECAP, b) S1 after ECAP*

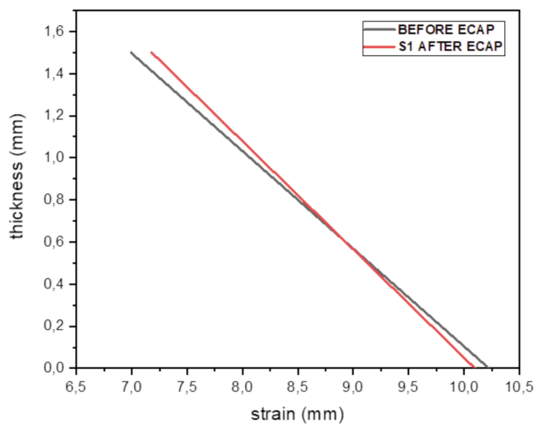


Figure 19. *The true strain/thickness graph for sheet before ECAP and S1 after ECAP*

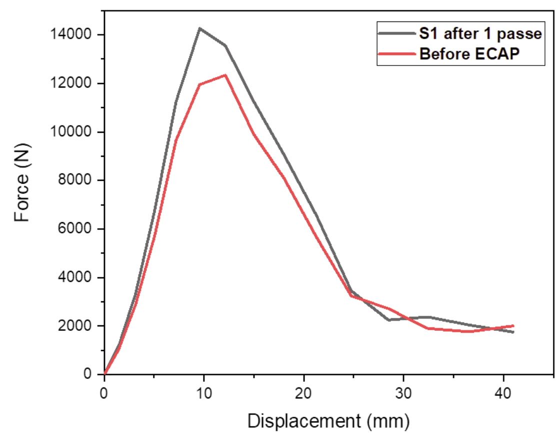


Figure 20. *Representation of the punch load (N)-Displacement (mm) curve*

quantitative analysis of Kamikawa et al. [39] .Comparing the behavior of segments a-c (before ECAP) and b-c (S1 after ECAP), we observe that the reduction in punch load is more rapid after ECAP, indicating that the sheet's behavior post-ECAP is less ductile due to the increase in microhardness. The results of this simulation correlate with the experimental results.

4. Conclusions

This experimental work investigates the effect of equal channel angular pressing (ECAP) on the drawability of multilayered DC04 steel sheets. The ECAP die used has a channel with an interior angle of Φ=120° and an exterior angle of Ψ=10°. The main conclusions from this study are as follows:

The study demonstrated significant improvement in microhardness for the inner layer of the ECAP-extruded material, which increased from 120 to 197.4 HV (64%), with slight increases observed in the other layers. The decrease in the standard deviation of the microhardness measurements after ECAP indicates improved structural homogeneity. Finite element simulations with Abaqus showed a non-uniform stress distribution during ECAP, with the maximum stress concentrated on the inner layer.

Microstructural analysis revealed a 70% reduction in average grain size in the inner layer, resulting in a more uniform structure with a light texture. X-ray diffraction confirmed this reduction in grain size without any phase change. Tensile tests showed an increase in yield stress by 20% and ultimate tensile strength by 8.3%, while plastic elongation, strain hardening exponent, and strain hardening exponent decreased by 27%, 10.17%, and 52.17%, respectively.

The Erichsen test results showed a 10.2% reduction in the Erichsen Index after ECAP, consistent with maintaining good drawability, with cracks forming in an arc shape both before and after ECAP. No correlation was found between the work hardening coefficient and the IE parameter. The simulation results from the Erichsen tests showed three different stress zones and highlighted the less ductile behavior of the material after ECAP.

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Author contribution

The study design and drafting of the manuscript were realized by all authors. The material preparation, data collection, and analysis were carried out by Massil Talantikite, Abdelmalek Mebarek, Mohamed Zaaf and Saida Boukeffa. All authors have read and approved the final manuscript.

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Conflict of interest

The authors declare no competing interest.

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UTICAJ JEDNOKANALNOG UGAONOG PRESOVANJA NA DUBOKO IZVLAČENJE LIMA OD DC04 ČELIKA

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Apstrakt

Jednokanalno ugaono presovanje (ECAP) je tehnika intenzivne plastične deformacije (SPD) koja izaziva značajne promene u kristalnoj strukturi materijala, što dovodi do poboljšanja mehaničkih svojstava. Cilj ovog eksperimentalnog rada je ispitivanje uticaja ECAP-a na sposobnost dubokog izvlačenja limova od čelika DC04. Uzorak sastavljen od šest slojeva lima deformisan je na sobnoj temperaturi, koristeći unutrašnji ugao kanala od 120° u jednom prolazu. Karakterizacija je sprovedena merenjem tvrdoće i ispitivanjem zatezanja, uz primenu optičke mikroskopije i analize rendgenskom difrakcijom (XRD). Pored toga, izvršena je simulacija metodom konačnih elemenata u softveru Abaqus. Testom prema Erichsenu procenjena je sposobnost dubokog izvlačenja lima sa najboljim mehaničkim svojstvima. Rezultati su pokazali značajno povećanje mikrotvrdoće, sa poboljšanjem od 64% u odnosu na početnu vrednost. Mikrostrukturna analiza ukazala je na smanjenje veličine zrna za 70%, uz blagu pojavu teksture i bez faznih promena. Ispitivanja zatezanjem pokazala su porast granice razvlačenja (Re) i zatezne čvrstoće (Rm), uz istovremeno smanjenje izduženja (A%) i eksponenta ojačavanja deformacijom (n). Test prema Erichsenu pokazao je blago smanjenje indeksa izvlačenja (IE) za 10%. Sveukupno, postignuto je poboljšanje mehaničkih svojstava limova od čelika DC04 uz očuvanje dobre sposobnosti dubokog izvlačenja.

Ključne reči: *ECAP; Duboko izvlačenje; Erichsen test; Limovi od čelika DC04; Simulacija; Tehnologije proizvodnje*