Düzce University Journal of Science & Technology, 11(2023) 2309-2320

Düzce University
Journal of Science & Technology

Research Article

Determination of Modified Mohr-Coulomb Damage Model Parameters for DH780 Steel in Finite Element Analysis

Tolgahan CİVEK[a] , Nuri SEN [a,*], Oktay ELKOCA[a]

[a] *Department of Mechanical Engineering, Faculty of Engineering, Düzce University, Düzce, TURKEY*
* *Corresponding author's e-mail address: nurisen@duzce.edu.tr*
DOI: 10.29130/dubited.1390682

ABSTRACT

In sheet metal forming processes, tearing problems might be occasionally encountered due to many reasons such as incorrect forming parameters. The trial and error methods that are used to solve such problems, on many occasions, are time-consuming and inefficient in terms of finding the correct forming parameters or die design for the forming process. The finite element analysis method, on the other hand, can be used as a tool that is both time and cost-saving. However, in order to effectively exploit the use of finite element analysis in sheet metal forming operations, the material that is used to be formed needs to be well characterized in terms of its hardening behaviour and failure criteria. In this study, a TRIP-aided DP steel (DH780) has been tensile tested in three different deformation conditions (uniaxial, plane stress and shear) and the parameters of its hardening model (Hollomon) and failure criteria (Modified Mohr-Coulomb) have been determined. According to the simulation results, obtained hardening parameters are able to describe the flow behaviour of the steel and the used failure criterion is able to predict the experimental failure correctly in each deformation condition.

Keywords: *Finite element analysis, damage models, optimization, tensile test*

DH780 Çeliği için Modifiye Edilmiş Mohr-Coulomb Hasar Model Parametrelerinin Belirlenmesi

ÖZ

Sac metal malzemelerin şekillendirilmesinde uygulanılan prosesler sırasında karşılaşılan çeşitli hata veya kusurlar üretim maliyetini ciddi seviyelerde arttırmaktadır. Metal şekillendirme prosesinin sonlu elemanlar aracılığı ile önceden analiz edilmesi, üretimde deneme yanılma sayılarını ciddi oranda azaltıp, üretim maliyetinin önemli bir seviyede düşmesine yardımcı olmaktadır. Bu bağlamda, sonlu elemanlar analizlerinde deneysel sonuçlara yakınsamanın sağlanması için analizlerde malzemenin plastik davranışını tanımlayan akış modelinin ve aynı zamanda hasar tespiti için yararlanılan hasar modellerinin doğru bir şekilde tanımlanması ve parametrelerinin optimize edilmesi gerekmektedir. Bu çalışmada DH780 çelik malzeme için üç farklı deformasyon durumundaki (Kesme, tek eksenli çekme ve saf gerinim) numuneler çekme testine tabii tutulmuştur. Elde edilen verilerden yararlanılarak, Hollomon sertleşme modelinin ve modifiye edilmiş Mohr Coloumb hasar modellerinin parametreleri belirlenmiş ve optimize edilmiştir. Analiz ortamında yapılan çekme testlerinin sonuçları deneysel verilerle karşılaştırıldığında sonuçlar arasında yüksek oranda bir uyumun sağlandığı gözlemlenmiştir.

Anahtar Kelimeler: *Sonlu Elemanlar Analizi, Hasar Modolleri, Optimizasyon, Çekme Testi*

---

[1]11. Uluslararası Meslek Yüksekokulları Sempozyumu'nda (UMYOS) sunulmuştur.
Received: 14/11/2023, Revised: 25/11/2023, Accepted: 08/12/2023

I. INTRODUCTION

Sheet metal forming methods involve stretching or drawing of sheets by a punch into a desired shape through a counter die [1]. However, even small changes in the forming parameters such as die radius, the amount of blankholder force, drawing bead design and etc. can have a significant impact on whether the forming process will be successful or not [2]. Hence, optimizing the forming parameters through trial and error method might cause significant waste both in time and cost [3]. Implementing the Finite Elements Method (FEM) in the forming processes, can drastically improve the forming process since it allows to visualize the problems and let the related parameters to be changed earlier in the die design process [3].

In order to use FEM effectively to observe the possible forming problems, it is required to well characterize the forming sheet metal [4]. The hardening model of the sheet metal is one of the most important parameters that is essential to correctly determine since it describes how the sheet metal flows during a forming operation. Hollomon, Swift, Fields & Backofen and Voce are some examples of isotropic hardening models that are commonly used in sheet metal forming simulations [5]–[10]. Depending on the flow behaviour of the sheet metal, the hardening model needs to be selected accordingly and its parameters need to be optimized. For some materials, the flow resistance might be different along the rolling direction (RD), diagonal direction (DD), and transversal direction (TD) of the sheet metal, which is called anisotropy [11], [12]. The anisotropic behaviour can cause an earing profile in the drawn sheet metals, changing the height of the drawn shapes to be different along the different directions of the sheet metal [13], [14]. For such materials, a kinematic hardening model may need to be selected and their parameters need to be optimized in order to visualize the correct flow behaviour of the sheet metal [15], [16]. To visualize the regions, where the sheet metal is likely to suffer from critical damage, in FEM simulations, it is necessary to implement a failure criterion for the defined sheet metal. Forming Limit Diagram (FLD) is one of the most known popular failure criterion that is used in FEM simulations [17]–[19]. FLD is simply a diagram which separates the safe straining zone from the critical straining zone, where the splitting occurs. By defining the FLD in the FEM simulation, critical zones in the sheet metal can be observed during a forming simulation. However, this method requires excessive amounts of tests in order to fully create a FLD [20]. Additionally, the accuracy of the FLD lowers for forming processes in which the strain path changes [21]. In order to overcome the inaccuracy related to the strain path changes in FLD, stress-based FLD methods can be used [22], [23].

Damage models are used to predict the onset of fracture in the sheet metal by relating various parameters such as hydrostatic stress, stress triaxiality, lode angle, etc. to the failure strain [24]. In its un-deformed state, the damage variable, D, in the sheet metal is assumed to be zero, D=0. As the forming process progresses, the damage accumulates in the sheet metal and if it reaches unity, D=1, or a critical damage value $D = D_{critical}$, the fracture takes place [24]. The damage variable can either be coupled or uncoupled to the strain hardening curve of the sheet metal [25], [26]. In coupled models, the damage variable affects the strain hardening curve and deteriorates the strain hardening of the sheet metal, while in uncoupled models the damage variable does not affect the strain hardening of the sheet metal and the damage accumulates independently from the strain hardening. While coupled models are more accurate in their prediction capabilities, the implementation of the uncoupled damage models and the determination of their parameters are much easier as compared to the coupled damage models [26]. Johnson Cook [27], Modified Mohr-Coulomb [28], Hosford-Coulomb [29], Lemaitre [30], Cockroft-Latham [31], and Gurson [32], are some examples of damage models that can be implemented in FEM simulations. Each model consider damage variable in terms of different material-dependent or independent parameters. For example, Johnson Cook model considers the effects of stress triaxiality, strain rate and temperature [27], Modified Mohr-Coulomb and Hosford-Coulomb models consider the effects of stress triaxiality and lode angle [28], [29], Lemaitre model considers the critical damage in uniaxial tension test [30], Cockroft-Latham model considers the maximum principal stress [31], Gurson model considers the void volume fractions [32]. Depending on how these parameters affect the formability of the sheet metal, the most feasible damage model can be selected.

In this study, a TRIP-aided DP steel (DH780) has been tensile tested in terms of three different deformation modes (uniaxial, plane stress and shear) in order to test the material in three different stress triaxiality and lode angles. The flow curve in uniaxial tension and the elongation values in three different deformation modes have been used to obtain the parameters of the Hollomon hardening model and the Modified Mohr-Coulomb damage models. Tensile test simulations have been carried out in order to validate the hardening and damage model parameters.

II. EXPERİMENTAL METHODS

2.1. MATERIAL

In this study, DH780 TRIP-aided DP steel in 1.9 mm thickness was used. The microstructure of the steel consists of ferrite, martensite, bainite and retained austenite structures [33]. The chemical composition of the steel is given in Table 1 [34]. Uniaxial, Plane Stress and Shear test specimen geometries were cut from the sheet metal by water jet cutting method. The dimensions of the cut specimens are shown in Figure 1. Zwick/Roell uniaxial tension machine was used to test each samples. The test speed was 25 mm/min for each test samples. A strain extensometer with a gauge length of 50 mm was used to record the strain changes in the samples.

Table 1. *The chemical composition of DH780 steel* [34]

C	Si	Mn	P	S	Al	Nb	Cr	Ti	Cu	Ni	Mo	V
0.159	0.301	1.83	0.018	0.003	0.668	0.002	0.242	0.005	0.022	0.036	0.039	0.007

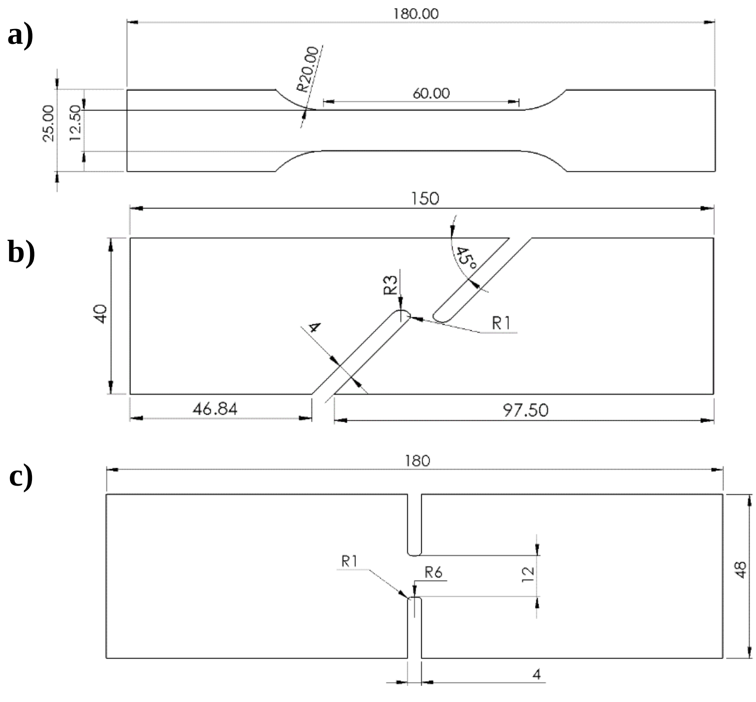


Figure 1. *The dimensions of the* ***a)*** *uniaxial,* ***b)*** *shear and* ***c)*** *plane stress test specimens*

2.2. HARDENING AND DAMAGE MODEL

The Hollomon hardening model was used in the simulations to predict the flow behaviour of the sheet metal. Hollomon hardening model is a model that is frequently used for its simplicity to predict the flow behaviour of sheet metals at room temperatures. The hardening model is given in Equation 1. The hardening parameter, K, and the strain hardening exponent, n, is found from the slope of log true strain and log true stress curve as given in Equation 2. and shown in Figure 2.

$$\sigma = K\epsilon^n \tag{1}$$

$$\log\sigma = n\log\epsilon + \log K \tag{2}$$

where σ is equivalent stress.

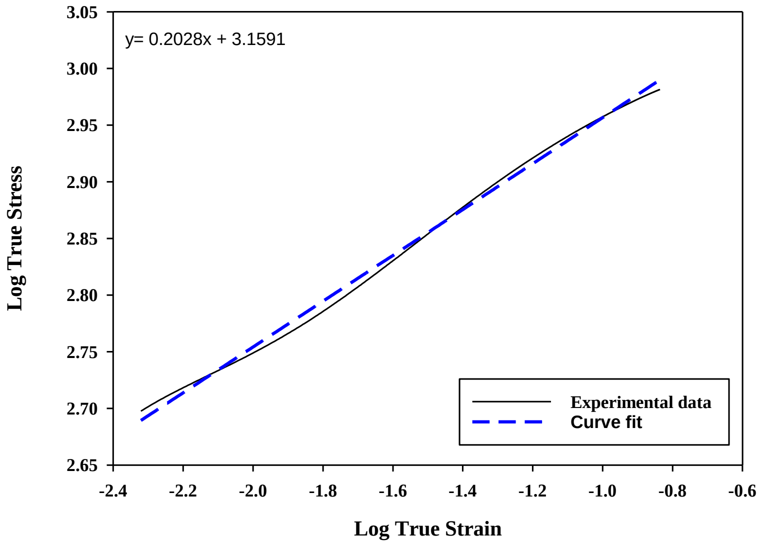


Figure 2. *The slope of Log true strain and log true stress graph of DH780 steel*

Modified Mohr-Coulomb (MMC) damage model was used to predict the onset of fracture for the sheet metal. MMC damage model considers the effects of stress triaxiality and the lode angle parameter on the formability of sheet metal to predict the onset of fracture. The stress triaxiality is known as one of the important factors impacting the ductility of sheet metals, especially under high stress triaxiality values. However, in recent studies, it has been shown that under low stress triaxiality values lode angle parameter has a significant effect on the ductility of sheet metals [35]. Geometrically, the lode angle can be described as the smallest angle in between the pure shear stress state and the projection of the stress tensor on the deviatoric plane. The lode angle value ranges in between $0^{\circ} < \theta < 60^{\circ}$ and the normalized lode angle parameter $-1 < \bar{\theta} < 1$. In case of uniaxial, plane stress and shear stress states, the lode angle parameter, respectively, takes the values of 1, 0 and 0 [35]. The formulations of the stress triaxiality, lode angle, normalized lode angle or lode angle parameter, and the MMC damage model are given in Equations 3-6., respectively.

$$\eta = \frac{\sigma_m}{\sigma_{vM}} \tag{3}$$

$$\theta = \frac{1}{3}\arccos(\zeta) \tag{4}$$

$$\overline{\theta} = 1 - \frac{6\theta}{\pi} = 1 - \frac{2}{\pi}\arccos(\zeta) \tag{5}$$

where η, σ_m and σ_{vM} respectively represent the stress triaxiality, mean stress and von misses stress, θ, ζ, and $\overline{\theta}$ represent the lode angle, normalized deviatoric invariant and lode angle parameter, respectively.

$$\bar{\epsilon}_f = \left\{\frac{A}{C_2}\left[C_\theta^s + \frac{\sqrt{3}}{2-\sqrt{3}}\left(C_\theta^{ax} - C_\theta^s\right)\left(\sec\left(\frac{\bar{\theta}\pi}{6}\right) - 1\right)\right] x \sqrt{\frac{1+C_1^2}{3}} \cos\left(\frac{\bar{\theta}\pi}{6}\right) + c_1\left(\eta + \frac{1}{3} sin\left(\frac{\bar{\theta}\pi}{6}\right)\right)\right\}^{-\frac{1}{n}} \quad (6)$$

where $\bar{\epsilon}_f$ represent the failure strain, the parameters A and n represent the parameters in the hardening model, c_1 describes the dependency of fracture strain on the triaxiality, c_2 influences the height of the fracture surface, C_θ^s describes the amount of lode angle dependency of the fracture surface, C_θ^{ax} controls the asymmetry of fracture surface with respect to lode angle parameter and is taken as 1 for $\bar{\theta} > 0$.

2.3. FINITE ELEMENT ANALYSIS MODEL

In this study, Simufact Forming 2023.2 was used to simulate the tensile tests. Test specimen geometries and the grips that are used to hold the specimens were exported to the software as shown in Figure 3. Specimens were meshed with sheet meshes in 0.87 mm size, meshes in the gauge sections of the specimens were refined by two times to create a fine mesh geometry. The through-thickness direction of the specimens was discretised by three mesh elements. Glue type contact was used in between the grips and the specimens. The upper grip, holding the specimen, was used to stretch the specimens at 25 mm/min velocity.

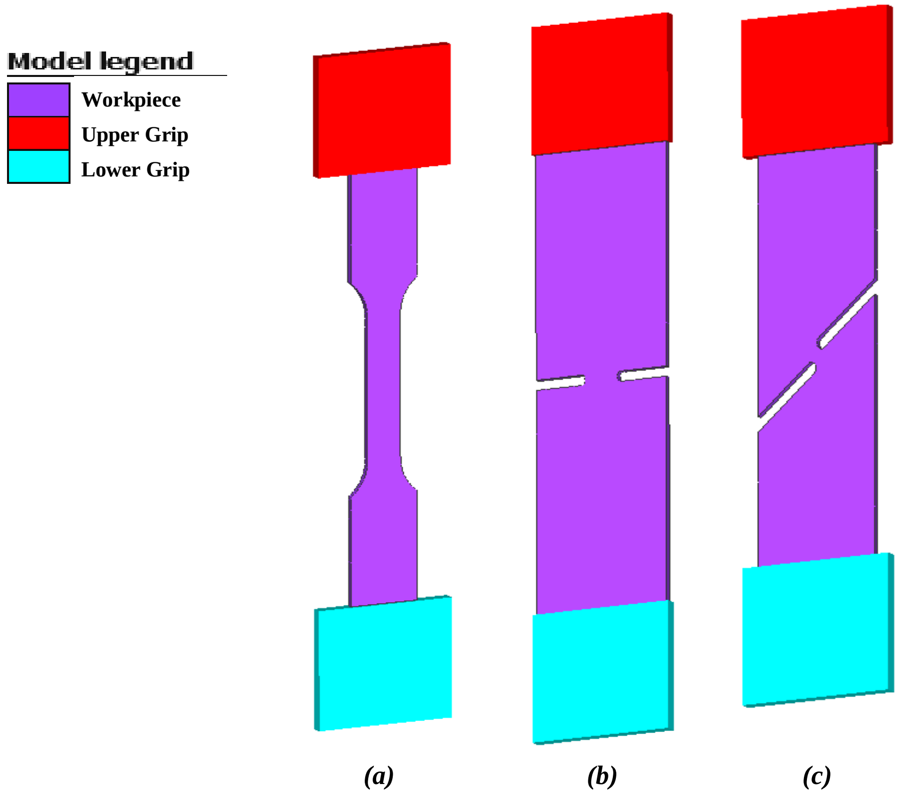
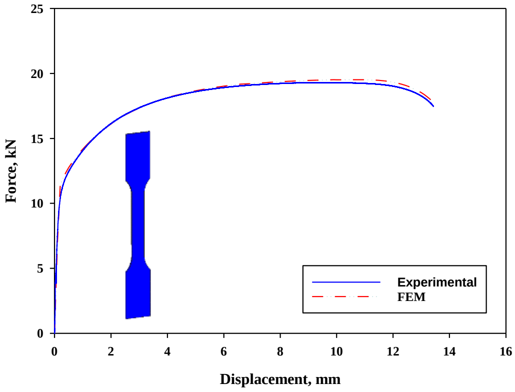


Figure 3. *Simulation model used in the analysis for a) uniaxial, b) plane stress, c) shear specimens*

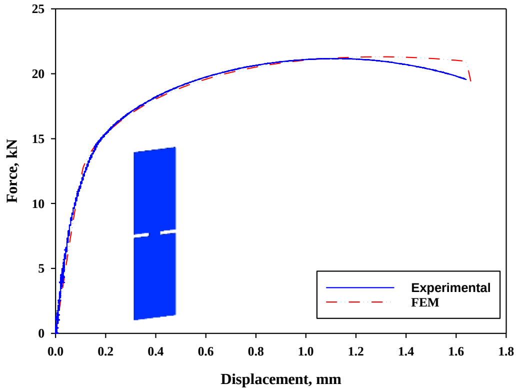
III. RESULTS AND DISCUSSIONS

3.1. HOLLOMON HARDENING MODEL

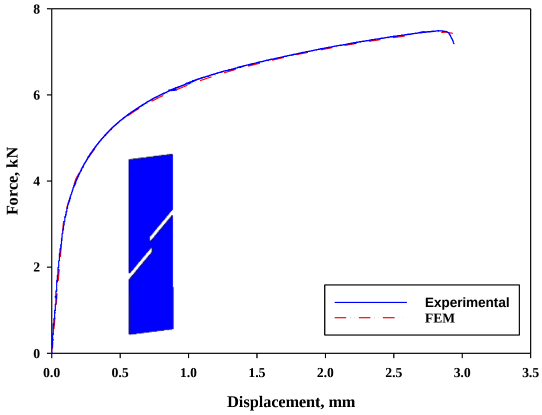
A hardening model is used to predict the flow behaviour of sheet metal. Thus, its correct input is essential to simulate the real sheet metal flow during the forming operation. The initial values of the hardening parameters that are obtained through Figure 2., may not directly result in true flow behaviour. Thus, it is necessary to use the reverse analysis method to find the optimum hardening parameters that represent the flow behaviour of the sheet metal. In order to evaluate the fitness of the hardening model, tensile test experiments are conducted in the FEM simulations and the obtained force-displacement curves are compared with the experimental values. The obtained hardening model parameters are as follows: K= 1305, n= 0.166, and the comparison graphs of the simulated and the experimental force-displacement curves are shown in Figure 4. It can be seen that the Hollomon hardening model that is implemented in the simulation is sufficient to accurately predict the flow behaviour of DH780 steel for uniaxial, plane stress and shear test specimens.



(a)



(b)



(c)

Figure 4. *The force-displacement curves for* ***a)*** *uniaxial,* ***b)*** *plane stress and* ***c)*** *shear test specimens*

3.2. MMC DAMAGE MODEL

Damage models in FEM analysis are used to inspect the regions in the sheet metal where the failure is likely to occur. In many studies, it is mentioned that the stress triaxiality and the lode angle have a significant effect on the formability of sheet metals [36], [37]. Thus, in this study, the MMC damage model, which considers the effects of stress triaxiality and lode angle, is used to determine its parameters for DH780 steel. For this reason, FEM simulations have been carried out for uniaxial, plane stress and shear test specimens and the critical elements, which the crack first initiates, have been tracked to determine the critical strain, average stress triaxiality and the lode angle parameters. The variation of the lode angle parameter in uniaxial, plane stress and shear specimens at the critical element has been shown in Figure 5. It can be seen that the lode angle parameter value for the uniaxial specimen has been $\overline{\theta} = 1$, while the values for plane stress and shear specimens have varied around $\overline{\theta} \approx 0$. The variation of the stress triaxiality values in uniaxial, plane stress and shear specimens at the critical element have been shown in Figure 6. It can be seen that the stress triaxiality value for the uniaxial specimen has been $\eta = 0.33$, while the stress triaxiality values for plane stress and shear specimens have varied around $\eta \approx 0.56$ and $\eta \approx 0$, respectively. The average stress triaxiality, lode angle parameter and the critical strain values have been given in Table 2. Using the values in Table 2., the parameters of the MMC damage model have been obtained and the values have been optimized by the reverse analysis method. The optimised MMC damage model parameters and the fracture surface have been given in Table 3., and Figure 7., respectively. The fractured simulation results in uniaxial, plane stress and shear modes have been shown in Figures 7, 8 and 9, respectively. The fracture initiation or the mesh separation has started at the centre of all the specimens. It is seen that the optimized MMC damage model parameters for DH780 steel have been able to accurately predict the onset of fracture in all the specimens.

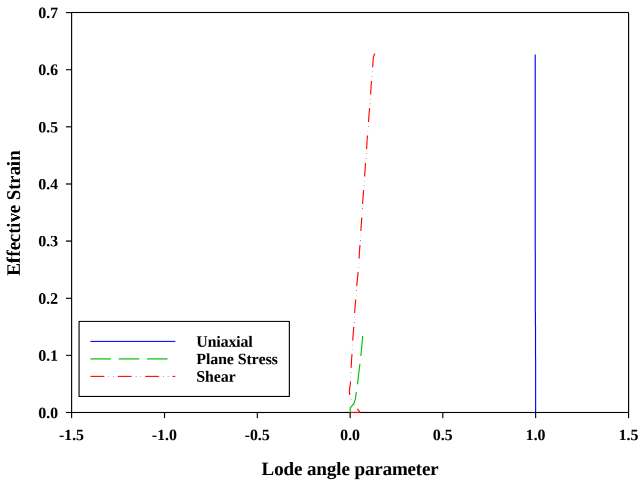


Figure 5. *The variation of the lode angle parameter at the critical element in uniaxial, plane stress and shear tests.*

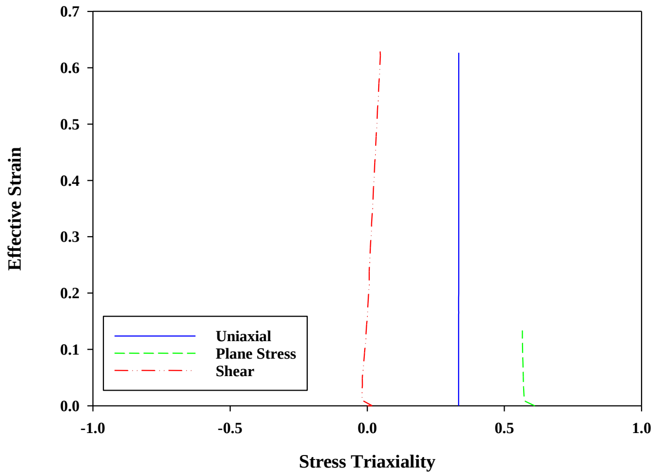


Figure 6. *The variation of the stress triaxiality at the critical element in uniaxial, plane stress and shear tests.*

Table 2. *The average stress triaxiality, lode angle parameter and the critical strain values for uniaxial, plane stress and shear test specimens*

Specimen	Stress Triaxiality	Lode angle Parameter	Critical Strain
Uniaxial	0.33	1	0.75
Plane Stress	0.57	0.08	0.26
Shear	0.05	0.15	0.76

__Table 3.__ The optimized MMC damage model parameters used in the simulations.

A	n	c_1	c_2	C_θ^s	C_θ^{ax}
1305	0.166	0.1526	735.648	1.0302	1

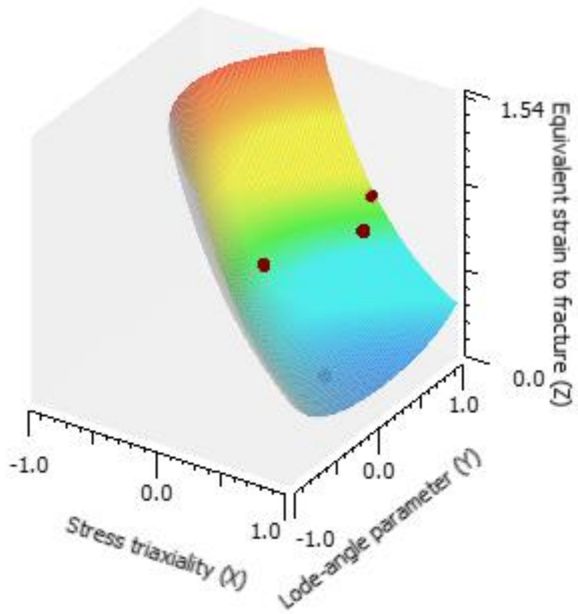
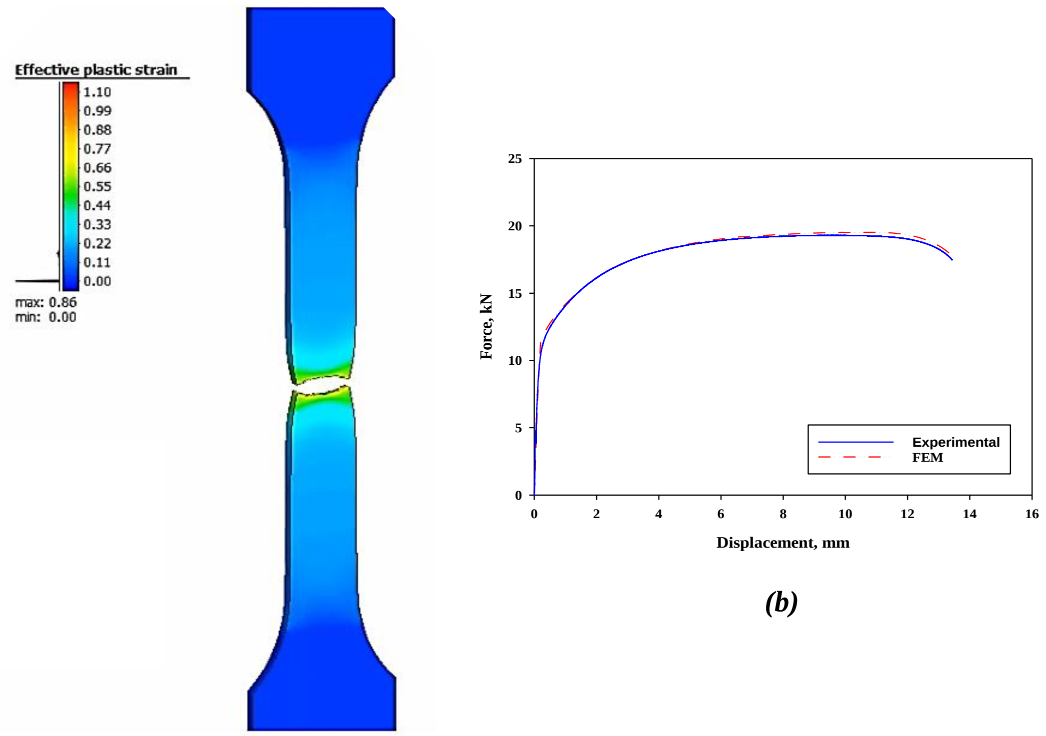


__Figure 7.__ The fracture surface of MMC damage model obtained for DH780 steel



(a)

*__Figure 8. (a)__ The fracture image of the uniaxial test specimen and **(b)** the respective force-displacement curve*

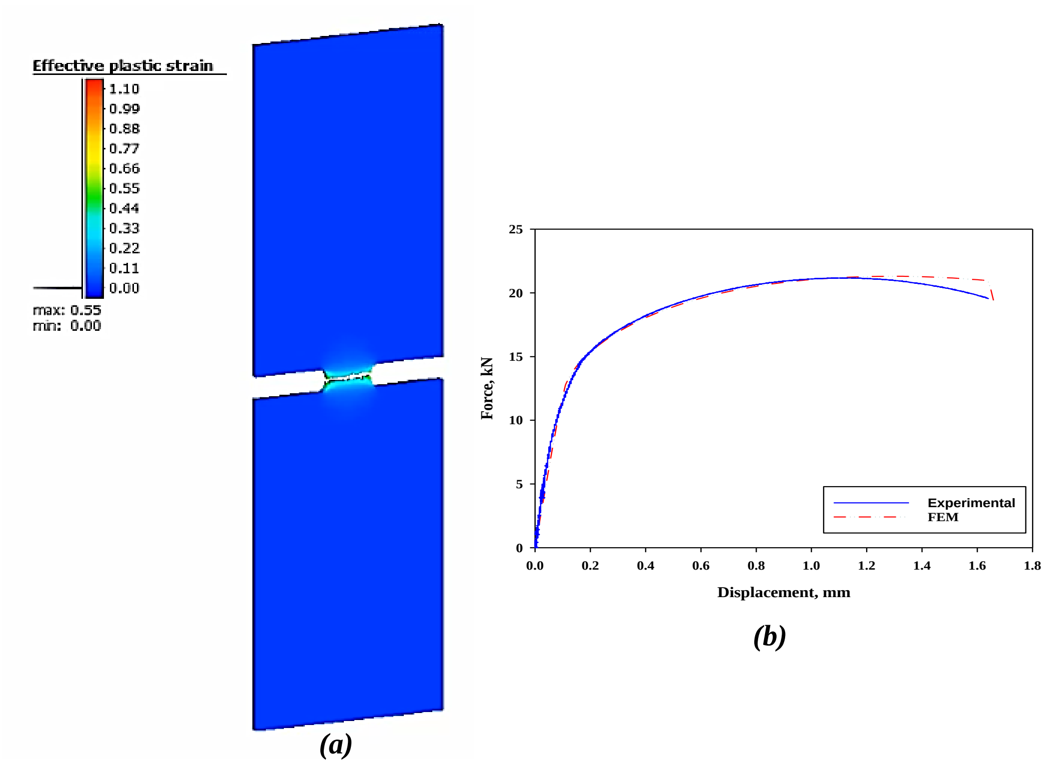


Figure 9. (a) *The fracture image of the plane stress test specimen and* ***(b)*** *the respective force-displacement curve*

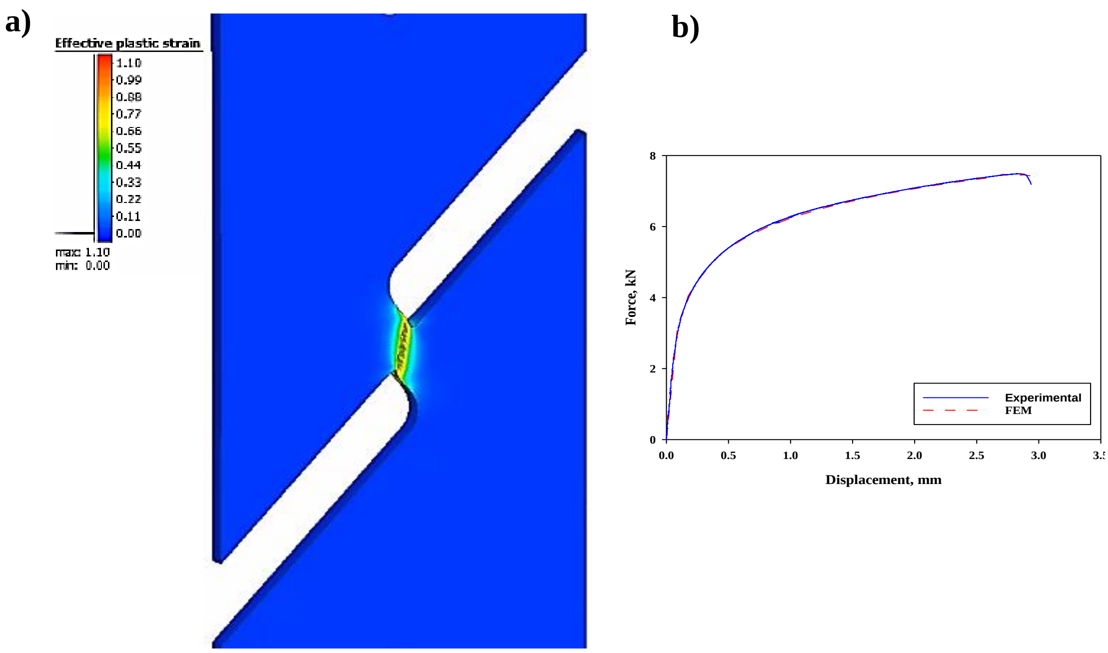


Figure 10. (a) *The fracture image of the plane stress test specimen and* ***(b)*** *the respective force-displacement curve*

IV. CONCLUSION

In this study, finite element analysis has been carried out to determine and calibrate the parameters of Hollomon hardening model and the Modified Mohr-Coulomb damage model for a TRIP-aided DP steel (DH780). The following conclusions can be drawn from the study:

- The determined Hollomon hardening model parameters have been able to describe the flow behaviour of the DH780 steel for uniaxial, plane stress and shear test specimens.
- The lowest elongation has occurred in the plane stress test sample.
- The determined Modified Mohr-Coulomb damage model parameters have been able to predict the onset of fracture in all the tests.
- Obtained MMC fracture surface has indicated that the effect of stress triaxiality has had a more prominent effect on the formability of DH780 steel than the lode angle parameter.

ACKNOWLEDGEMENTS: This work was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) (Project No: 222M321). The authors would like to thank TUBITAK for the financial support given to the project.

V. REFERENCES

[1] T. Altan and A. E. Tekkaya, *Sheet Metal Forming*. Ohio, United States: ASM International, 2012, pp. 1-201.

[2] J. Hu, Z. Marciniak, and J. Duncan, *Mechanics of sheet metal forming*. Oxford, United Kingdom: Elsevier, 2002, pp. 1-204.

[3] H. S. S. Aljibori and A. M. Hamouda, "Finite element analysis of sheet metal forming process," *European Journal of Scientific Research*, vol. 33, no. 1, pp. 57-59, 2009.

[4] N. Şen, T. Civek, Ö. İlhan, Ö. Erdem Yurt, M. H. Çetin, and H. Şimşir, "Prediction of Flow Behavior and Deformation Analysis of AA5754 Sheet Metal at Warm and Hot Temperatures", *J. Mater. Eng. Perform.*, pp. 1–12, 2023.

[5] M. Joun, I. Choi, J. Eom, and M. Lee, "Finite element analysis of tensile testing with emphasis on necking", *Comput. Mater. Sci.*, vol. 41, no. 1, pp. 63–69, 2007.

[6] B. M. Chaparro, M. C. Oliveira, J. L. Alves, and L. F. Menezes, "Work hardening models and the numerical simulation of the deep drawing process", *Materials Science Forum*, vol. 455, pp. 717–722, 2004.

[7] W. Jia, S. Xu, Q. Le, L. Fu, L. Ma, and Y. Tang, "Modified Fields–Backofen model for constitutive behavior of as-cast AZ31B magnesium alloy during hot deformation", *Mater. Des.*, vol. 106, pp. 120–132, 2016.

[8] J. Shen, L. Hu, Y. Sun, Z. Wan, X. Feng, and Y. Ning, "A comparative study on artificial

neural network, phenomenological-based constitutive and modified Fields–Backofen models to predict flow stress in Ti-4Al-3V-2Mo-2Fe alloy", *J. Mater. Eng. Perform.*, vol. 28, pp. 4302–4315, 2019.

[9] H. Zhang, C. Xu, T. Gao, X. Li, and H. Song, "Identification of strain hardening behaviors in titanium alloys using tension tests and inverse finite element method", *J. Mech. Sci. Technol.*, vol. 37, no. 7, pp. 3593–3599, 2023.

[10] J.-H. Kim, A. Serpantié, F. Barlat, F. Pierron, and M.-G. Lee, "Characterization of the post-necking strain hardening behavior using the virtual fields method", *Int. J. Solids Struct.*, vol. 50, no. 24, pp. 3829–3842, 2013.

[11] G. Rousselier, F. Barlat, and J. W. Yoon, "A novel approach for anisotropic hardening modeling. Part I: Theory and its application to finite element analysis of deep drawing", *Int. J. Plast.*, vol. 25, no. 12, pp. 2383–2409, 2009.

[12] Y. Zhang, Y. Duan, P. Fu, S. Qi, and J. Zhao, "Constitutive modeling based on non-associated flow rule for anisotropic sheet metals forming", *Mater. Today Commun.*, p. 107086, 2023.

[13] K. Gök, H. Taş, A. Gök, and M. A. Alkan, "Investıgatıon usıng fınıte element analysıs of effect to earrıng of anısotropy parameters ın deep drawıng process", *Int. J. Mod. Manuf. Technol.*, vol. 15, no. 1, 2023.

[14] P. Fu *et al.*, "Finite element simulation and experimental study of non-blank holder forward and backward composite deep drawing earing test", *Int. J. Adv. Manuf. Technol.*, pp. 1–16, 2023.

[15] A. Sanrutsadakorn, W. Lawong, and W. Julsri, "Numerical Study of Predicting Forming Process Based on Different Hardening Models in Advanced High Strength Steel Sheets", *Key Eng. Mater.*, vol. 951, pp. 21–32, 2023.

[16] M. U. Sikandar and M. Usama, "A Case Study in Deep Drawing Process: Numerical Simulation and Analysis of Material Behavior and Hardening Models", *Young*, vol. 7, pp. 10–19.

[17] A. Rouzbeh, R. Hashemi, and M. Sedighi, "Experimental and numerical study of microstructure, mechanical characteristics, and forming limit curve for Al 1050/Mg-AZ31B two-layer sheets manufactured via roll bonding technique", *J. Alloys Compd.*, vol. 942, p. 169059, 2023.

[18] M. Habibi, R. Hashemi, A. Ghazanfari, R. Naghdabadi, and A. Assempour, "Forming limit diagrams by including the M–K model in finite element simulation considering the effect of bending", *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 232, no. 8, pp. 625–636, 2018.

[19] M. Habibi, A. Ghazanfari, A. Assempour, R. Naghdabadi, and R. Hashemi, "Determination of forming limit diagram using two modified finite element models", *Mech Eng*, vol. 48, no. 4, pp. 141–144, 2017.

[20] T. Pepelnjak and K. Kuzman, "Numerical determination of the forming limit diagrams", *J. Achiev. Mater. Manuf. Eng.*, vol. 20, no. 1–2, pp. 375–378, 2007.

[21] K. Achineethongkham and V. Uthaisangsuk, "Analysis of forming limit behaviour of high strength steels under non-linear strain paths using a micromechanics damage modelling", *Int. J. Mech. Sci.*, vol. 183, p. 105828, 2020.

[22] S. K. Paul, "Theoretical analysis of strain- and stress-based forming limit diagrams", *J. Strain Anal. Eng. Des.*, vol. 48, no. 3, pp. 177–188, 2013, doi: 10.1177/0309324712468524.

[23] C. H. M. Simha, R. Grantab, and M. J. Worswick, "Computational analysis of stress-based

forming limit curves", *Int. J. Solids Struct.*, vol. 44, no. 25–26, pp. 8663–8684, 2007.

[24] P. F. Liu and J. Y. Zheng, "Recent developments on damage modeling and finite element analysis for composite laminates: A review", *Mater. Des.*, vol. 31, no. 8, pp. 3825–3834, 2010.

[25] C. Y. Tang, J. P. Fan, and T. C. Lee, "Simulation of necking using a damage coupled finite element method", *J. Mater. Process. Technol.*, vol. 139, no. 1–3, pp. 510–513, 2003.

[26] P.-O. Bouchard, L. Bourgeon, S. Fayolle, and K. Mocellin, "An enhanced Lemaitre model formulation for materials processing damage computation", *Int. J. Mater. Form.*, vol. 4, pp. 299–315, 2011.

[27] M. E. Korkmaz, "Verification of Johnson-Cook parameters of ferritic stainless steel by drilling process: experimental and finite element simulations", *J. Mater. Res. Technol.*, vol. 9, no. 3, pp. 6322–6330, 2020.

[28] H. Talebi-Ghadikolaee, H. Moslemi Naeini, M. J. Mirnia, M. A. Mirzai, S. Alexandrov, and H. Gorji, "Experimental and numerical investigation of failure during bending of AA6061 aluminum alloy sheet using the modified Mohr-Coulomb fracture criterion", *Int. J. Adv. Manuf. Technol.*, vol. 105, pp. 5217–5237, 2019.

[29] M. B. Gorji and D. Mohr, "Predicting shear fracture of aluminum 6016-T4 during deep drawing: Combining Yld-2000 plasticity with Hosford–Coulomb fracture model", *Int. J. Mech. Sci.*, vol. 137, pp. 105–120, 2018.

[30] A. Kumar, A. K. Singh, A. Shrivastava, S. Mishra, and K. Narasimhan, "Shear modified Lemaitre damage model for fracture prediction during incremental sheet forming", *Int. J. Solids Struct.*, vol. 252, p. 111822, 2022.

[31] G. Fang, P. Zeng, and L. Lou, "Finite element simulation of the effect of clearance on the forming quality in the blanking process", *J. Mater. Process. Technol.*, vol. 122, no. 2–3, pp. 249–254, 2002.

[32] M. M. Shahzamanian and P. D. Wu, "Study of forming limit diagram (FLD) prediction of anisotropic sheet metals using Gurson model in MK method", *Int. J. Mater. Form.*, vol. 14, pp. 1031–1041, 2021.

[33] Z. Hu, K. Wang, and J. Guo, "Microstructure and mechanical property of a novel hot dip galvanized dual phase steel with high ductility",in *Journal of Physics: Conference Series*, vol. 2368, no. 1, pp. 12021, 2022.

[34] SSAB, (2023,12,21) *Docol 800DH Data Sheet* [Online]. Available: https://www.ssab.com

[35] K. Danas and P. Ponte Castañeda, "Influence of the Lode parameter and the stress triaxiality on the failure of elasto-plastic porous materials", *Int. J. Solids Struct.*, vol. 49, no. 11–12, pp. 1325–1342, 2012.

[36] Y. Bao, "Dependence of ductile crack formation in tensile tests on stress triaxiality, stress and strain ratios", *Eng. Fract. Mech.*, vol. 72, no. 4, pp. 505–522, 2005.

[37] T. Güzelderen, "Investıgatıon of varıatıon of trıaxıalty and lode angle parameter values ın sheet metal formıng processes", M.S. thesis, Mechanical Engineering, Middle East Technical University, Ankara, Turkiye, 2022.