www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 8, No: 2, 2021 (1429-1440)

El-Cezerî Journal of Science and Engineering
Vol: 8, No: 2, 2021 (1429-1440)

DOI: 10.31202/ecjse.938538

ECJSE

Makale / Research Paper

A Comparative Study On Deep Drawing Process And Autoform Simulations Of DX54D + Z And DX56D + Z Steels

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Received/Geliş: 18.05.2021 **Accepted/Kabul:** 29.07.2021

Abstract: A Sheet Metal Forming (SMF) process, especially deep drawing, is one of the manufacturing processes that commonly used in the automotive industry. Compared with casting and forging, the SMF process has several advantages, including lesser weight materials and broader variations in shape that can be made. The most important of the problems in the SMF process is the wrinkling phenomenon and tearing of sheet products. The wrinkle and tear occurs because of the mechanical properties of the material, product geometry, and blank holder force. The finite element based Computer-Aided Engineering (CAE) program AutoForm Plus R7 used in this article was used for analysis. Solidworks software was used during mold design. AutoForm is a highly productive software that provides high accuracy and reliable results, specially developed for the sheet metal forming mold industry, especially for the automotive industry. With AutoForm, multiple analyses were made by computational calculations, even before the mold production started, and with the help of these analyses, the closest to perfect mold outputs were obtained. In addition, optimum drawbead geometry and springback effect were analysed. The most suitable material was selected for the deep drawing product. DX54D + Z and DX56D + Z from continuously hot-dip coated steel flat products selected as analysis materials. As a result, the simulation reports obtained from this study were compared with many results in the literature. It is concluded that DX56D + Z sheet material can be used in deep drawing products without negative consequences such as tearing, wrinkling and shrinkage marks.

Keywords: Steel Sheet, forming, AutoForm, Simulation, Deep Drawing.

DX54D + Z ve DX56D + Z Çeliklerinin Derin Çekme İşlemi ve Autoform Simülasyonları Hakkında Karşılaştırmalı Bir Çalışma

Öz: Bir Sac Metal Şekillendirme (SMŞ) süreci, özellikle derin çekme, otomotiv endüstrisinde yaygın olarak kullanılan üretim süreçlerinden biridir. Döküm ve dövme ile karşılaştırıldığında, SMŞ işleminin daha az ağırlıklı malzemeler ve yapılabilecek daha geniş şekil varyasyonları dahil olmak üzere çeşitli avantajları vardır. SMŞ sürecindeki sorunlardan en önemlisi, tabaka ürünlerde kırışma olması ve yırtılmadır. Kırışıklık ve yırtılma, malzemenin mekanik özellikleri, ürün geometrisi ve boşluk tutucu kuvveti nedeniyle oluşur. Analiz için bu makalede, sonlu eleman tabanlı Bilgisayar Destekli Mühendislik (CAE) programı AutoForm Plus R7 kullanılmıştır. Kalıp tasarımı sırasında Solidworks yazılımı kullanılmıştır. AutoForm, özellikle otomotiv endüstrisi için sac şekillendirme kalıp endüstrisi için özel olarak geliştirilmiş, yüksek doğruluk ve güvenilir sonuçlar sağlayan son derece verimli bir yazılımdır. AutoForm ile kalıp üretimi başlamadan önce bile hesaplamalı hesaplamalarla çoklu analizler yapılmış ve bu analizler sayesinde mükemmele en yakın kalıp çıktıları elde edilmiştir. Ek olarak, optimum çeki topuzu geometrisi ve geri esneme etkisi analiz edilmiştir. Derin çekme ürünü için en uygun malzeme tespit edilmiştir. Analiz malzemeleri olarak seçilen sürekli sıcak daldırma kaplamalı çelik yassı ürünlerden DX54D + Z ve DX56D + Z. Sonuç olarak, bu çalışmadan elde edilen simülasyon raporları, literatürdeki birçok sonuçla karşılaştırılmıştır. DX56D + Z sac malzemenin, yırtılma, buruşma ve çekme izleri gibi olumsuz sonuçlar olmadan derin çekme ürünlerinde kullanılabileceği sonucuna varılmıştır.

Anahtar Kelimeler: Çelik sac, Şekillendirme, Autoform, Simülasyon, Derin Çekme.

Bu makaleye atıf yapmak için
Durmuş, H., Güneşgörmez, G., Çömez, N., Gül, C., "A Comparative Study On Deep Drawing Process And Autoform Simulations Of DX54D + Z And DX56D +Z Steels" El-Cezerî Fen ve Mühendislik Dergisi 2021, 8 (3); 1429-1440.

How to cite this article
Durmuş, H., Güneşgörmez, G., Çömez, N., Gül, C., "A Comparative Study On Deep Drawing Process And Autoform Simulations Of DX54D + Z And DX56D +Z Steels" El-Cezerî Journal of Science and Engineering, 2021, 8 (3); 1429-1440.
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1. Introduction

Deep drawing is frequently applied to form sheet metals that are used in several industrial applications such as automotive, kitchenware, TV monitors etc. [1, 2]. Deep drawing is used to be known as an experience based sheet metal forming process which includes trial-and-error method [1]. Ironing, galling, orange peeling, earing, tearing, and wrinkling are frequently encountered defects of the deep drawing process [3-5]. However, formability of a given material by deep drawing and evolution of the mentioned defects can be predicted by the finite element (FE) based simulation softwares, hence manufacturing costs can be reduced [6, 7]. Apart from predicting the potential failures, simulation techniques present material flow during the forming process, a detailed analyses of stress-, strain- and temperature-distribution, and help to determine forces for forming process [7].

Plastic deformation of a sheet metal generates the inhomogeneous residual stresses which cause an elastic springback effect. Springback behavior may cause deformation and distortion of deep-drawn parts [8]. Springback simulation can be fulfilled by implicit or explicit solutions. Implicit solution applies reverse nodal force and equivalent iteration. If the accuracy of the stress field -in particular for complicated parts- after forming is poor, implicit solution may be disadvantageous in terms of convergence problem. Although the explicit solution doesn’t experience a convergence problem, it needs more CPU time for a FE solution, besides it requires a reasonable nodal damping value to be known [9, 10]. Autoform software is widely employed for simulating the drawing process by FE method. It prefers a computational solution based on implicit integration due to the physical limitations of the explicit method [11]. Apart from predicting deep drawing defects such as wrinkling, tearing etc., Autoform computes the springback of deformed sheet metal [2].

2. Literature Summary

Gösling et al. [5] numerically analysed the problem of ironing of deep drawn DC04 steel by AutoForm-Solver^{plus}. They reported that the ironing can be predicted by finite element method with the material flow with a high accuracy. Gil et al. [12] investigated the effect of pressure dependent friction coefficient on numerical springback predictions of a DX54D mild steel, a HSLA380 and a DP780 high strength steel. They simulated both the forming and the springback processes by Autoform R3.1 finite element software. Greco et al. [13] studied the dynamic behaviour of deep drawn DP600 steel by FE based Autoform software and validated the numerical results with the experimental study. They reported that for accurate numerical results, it is essential to know accurate plastic behaviour of the material, and production process parameters. Hol et al. [14] modelled an automotive part made of DX54D steel in TriboForm software -a branch of Autoform- using different lubrication amounts, tool roughness and coatings of steel. They reported that the effect of friction on the part quality and overall production stability can be predicted by Autoform simulation.

This study aimed to simulate the deep drawing process of DX54D + Z and DX56D + Z steel sheets and to verify the failure predictions after the deep drawing process of mentioned sheet materials. In addition, optimum drawbead geometry and springback behavior were analysed.

3. Materials and Method

3.1. Material

DX54D+Z and DX56D+Z from continuously hot-dip coated steel flat products selected as analysis materials. The mechanical properties of the materials used in this study are given in Table 1.

Table 1. Material specifications

Standard	Quality	Warranty period of mechanical properties	Flow trace avoid the warranty period	R_e $R_{p0.2}$ N/mm^2	R_m N/mm^2	A_{80} (%) min.	r_{90} min.	n_{90} min.
EN10346	DX54D+Z	1 months	6 months	120-220	260-350	36	1.6	0.18
EN10346	DX56D+Z	1 months	6 months	120-180	260-350	39	1.9	0.21

3.2. FEM Analysis of Deep Drawing

FE simulations of deep drawing of the given materials were executed by Autoform software using mechanical properties which exist in the material data library of Autoform. The model of deep drawn product is given in Figure 1.

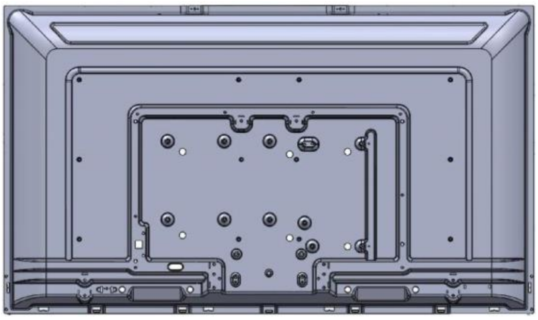


Figure 1. 3D model of deep drawn part

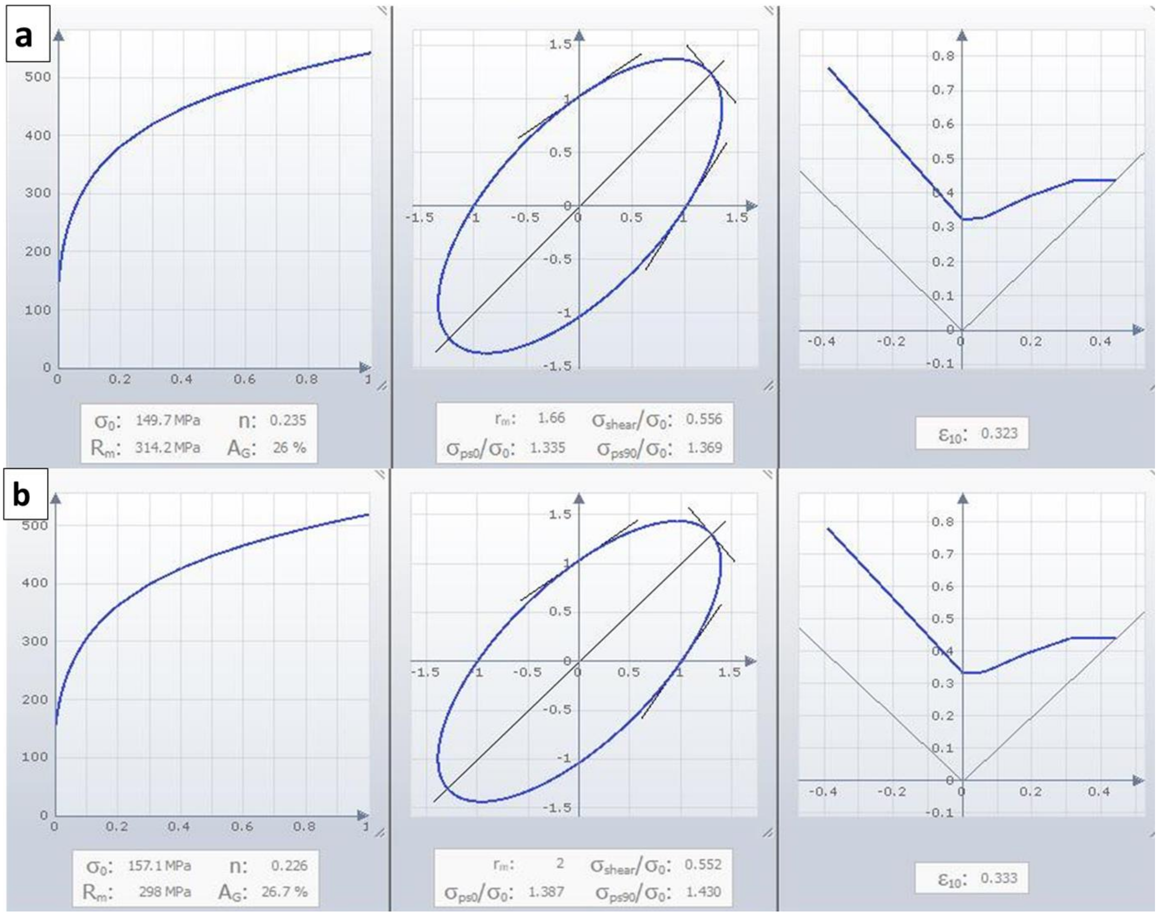


Figure 2. AutoForm graphical representation of material properties: strain rate and strain hardening, yield loci, FLC: a) DX54D+Z, b) DX56D+Z

Mechanical properties are listed in Table 2. Graphical representations of mechanical properties of materials are given in Figure 2. Industrial applications predicate Forming Limit Curve (FLC) criterion upon for the evaluation of ductile fracture during deformation. The level of the FLC depends on the n-value (strain-hardening exponent) and the sheet thickness [15, 16]. In this study, 0.6 mm thick steel sheets were employed.

The first analysis studies were carried out without the drawbead. The material which gave the most suitable Autoform simulation results was used for formability analysis in order to determine the optimum drawbead geometry. Thereafter, spring back analysis was carried out for the selected material using optimum drawbead geometry.

4. Results and Discussion

4.1. Pre-analysis Without Drawbead

In the first step of deep drawing simulations, the formability analyses were fulfilled without drawbead. Considering Figure 3 and the literature findings [17-20], it was experienced that a deep drawing process without drawbead would result in poor quality surfaces due to insufficient stress. The simulation was verified with the trial production of DX54D+Z steel sheet.

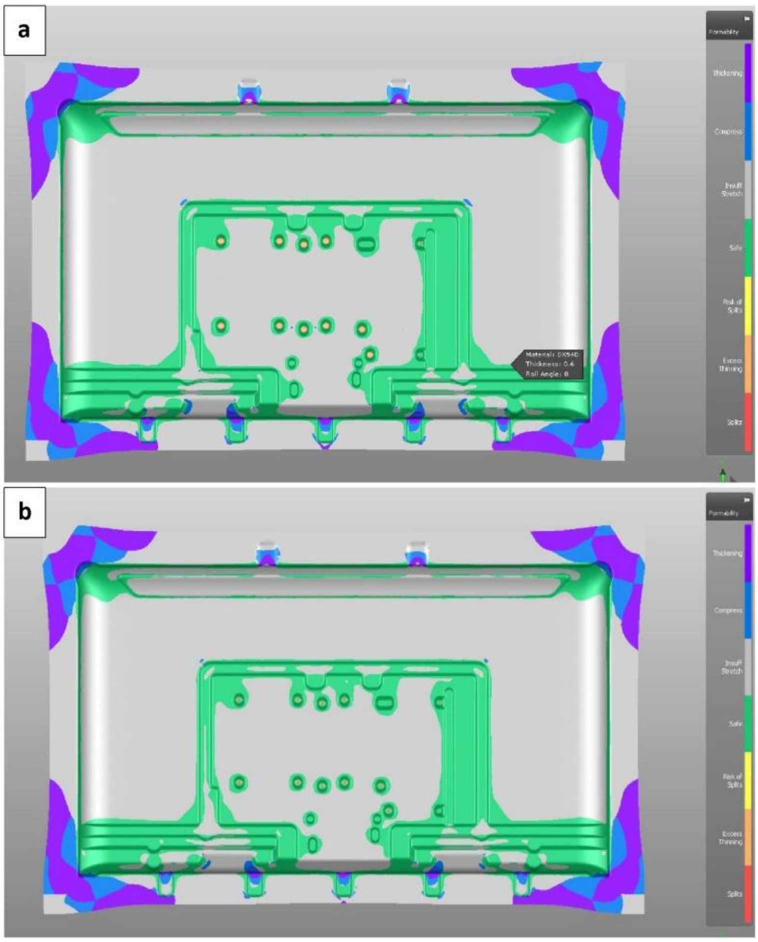


Figure 3. AutoForm formability analysis without drawbead a) DX54D + Z, b) DX56D + Z

The problems encountered in the deep drawing process without the drawbead were wrinkling circled with red, crush zones circled with yellow and tearing circled with blue as they were predicted by Autoform simulation (Figure 3a and Figure 4).

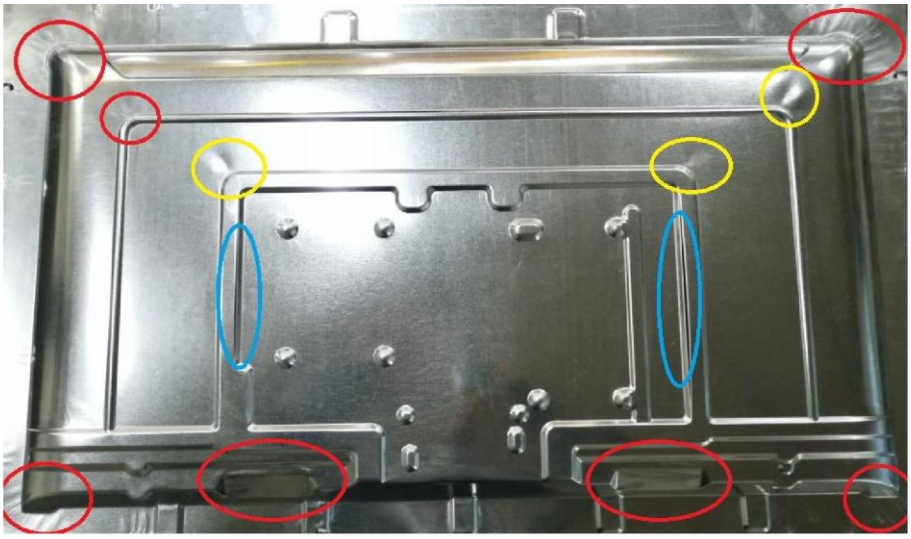
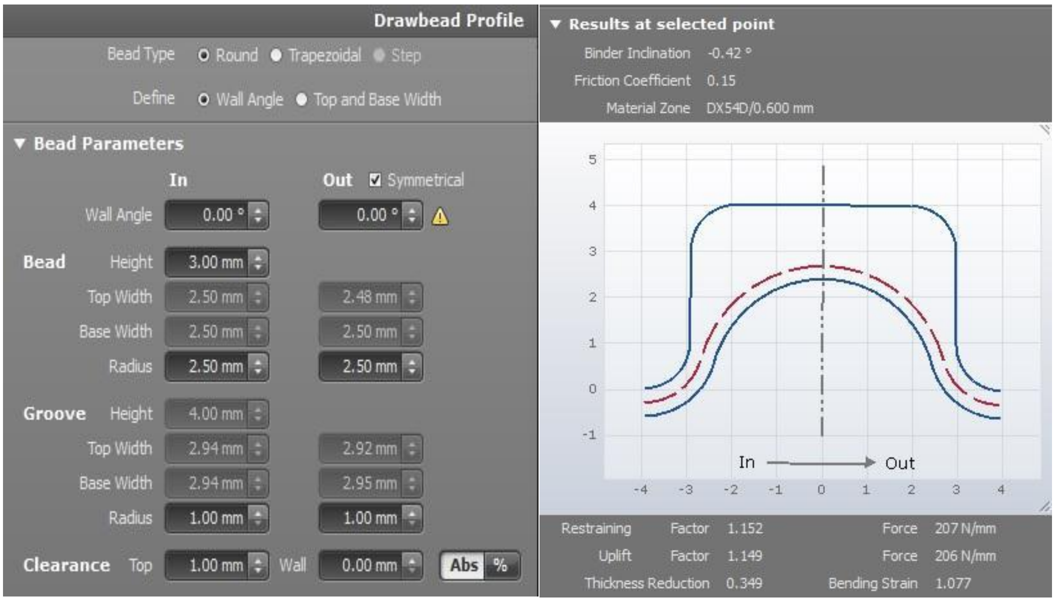


Figure 4. Problems encountered in deep drawing die output without drawbead (DX54D + Z)

4.2. Autoform Analysis Of Steel Sheets With Drawbead

After the drawbead data shown in Figure 5 was processed into the mold surfaces, it was analysed in the deep drawing process using the finite element method to examine the formability in two different material qualities that are frequently used in cold forming. The formability of each material was compared and deformation errors were evaluated through the formability limit diagrams obtained from these simulation studies.



Drawbead Profile

Bead Type ◉ Round ○ Trapezoidal ○ Step

Define ◉ Wall Angle ○ Top and Base Width

▼ **Bead Parameters**

		In	Out ☑ Symmetrical
	Wall Angle	0.00 °	0.00 ° ⚠
Bead	Height	3.00 mm	
	Top Width	2.50 mm	2.48 mm
	Base Width	2.50 mm	2.50 mm
	Radius	2.50 mm	2.50 mm
Groove	Height	4.00 mm	
	Top Width	2.94 mm	2.92 mm
	Base Width	2.94 mm	2.95 mm
	Radius	1.00 mm	1.00 mm
Clearance	Top	1.00 mm	Wall 0.00 mm

▼ **Results at selected point**

Binder Inclination -0.42 °
Friction Coefficient 0.15
Material Zone DX54D/0.600 mm

Restraining	Factor	1.152	Force	207 N/mm
Uplift	Factor	1.149	Force	206 N/mm
Thickness Reduction		0.349	Bending Strain	1.077

Figure 5. Drawbead profile results

Formability data obtained after analysis are given in Table 2 for each material grade. Based on these data, the material selection aimed for the study was realized. According to FLD of DX56D+Z, 88.84% of sheet metal area can be deformed fully-compatible with the mold shape. Thickening, crush and tearing were predicted 0.07%, 0.19%, and 0.01% of the area, respectively. Besides, risk of tearing was found to be 0.08% of the area. Although the safe forming area for DX54D+Z was predicted as 81.94%, tearing stepped forward with a value of 1.23% of area which was also observed along the female radius of the simulated deep drawn part (Figure 6a). The deep drawing simulation results of the given materials can be related with their mechanical properties. It was observed that the material with a higher yielding strength exhibits worse cold formability [21]. In addition, DX56D+Z experienced less thinning than DX54D+Z owing to its higher anisotropy (r-value) [Table 1].

Table 2. Comparison of materials according to Formability Limit Diagram (FLD) (%)

Material	DX54D+Z	DX56D+Z
Thickening	0.37	0.07
Crush	0.24	0.19
Insufficient stress	14.30	10.55
Safe	81.94	88.84
Risky	1.53	0.08
Over thinning	0.37	0.27
Tearing	1.23	0.01

Anisotropy determines the formability of materials. Hence it is an important factor for the deep drawing process. A high r-value provides better formability with less thinning of sheet metal [22]. Similarly, Tisza and Kovács [23] reported that higher anisotropy coefficient provides more favorable limit strain values especially for negative range of minor principal strain. In addition, they showed diagrammatically that the increasing n-value (strain hardening exponent) shifts the FLD curve upward, hence improves the formability of the material. Also, Lou et al. [24] reported that FLD linearly increases with increasing n-value. So, it can be stated that DX54D+Z material exhibited deep drawing failures depending on its worse formability due to its lower n-value in comparison with the DX56D+Z material.

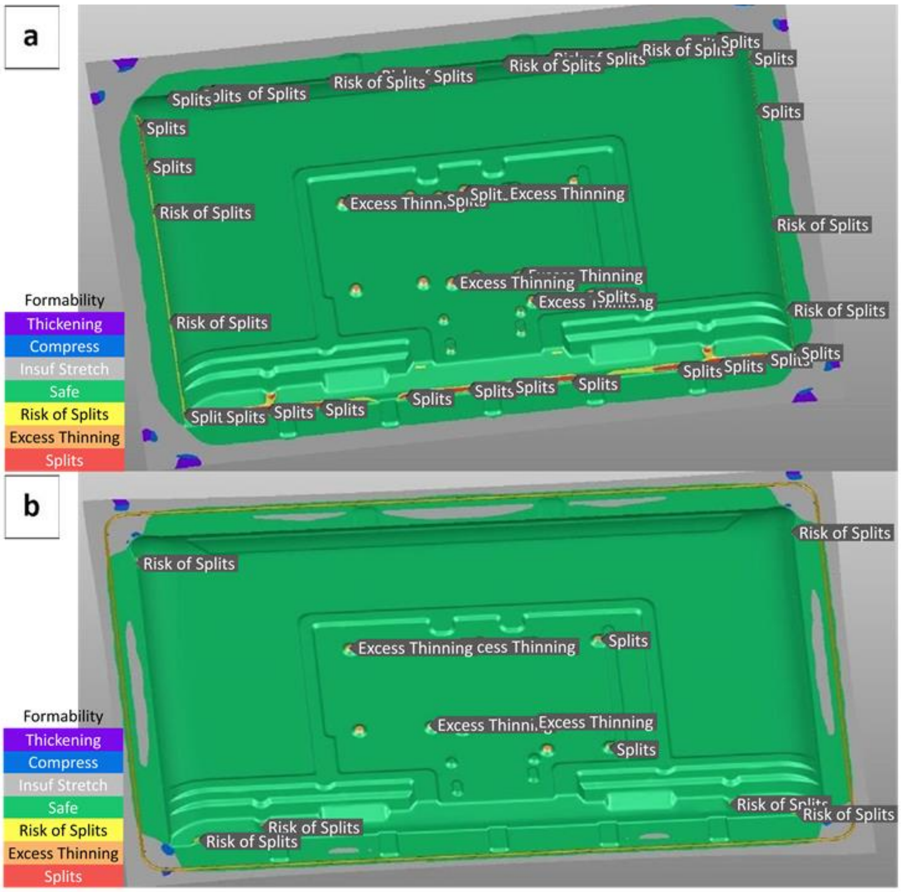


Figure 6. AutoForm formability analysis of: a) DX54D+Z, b) DX56D+Z

Trial deep drawing process of DX54D+Z resulted in tearing in several zones of the product (Figure 7a) which was predicted by Autoform analysis (Figure 6a). Figure 7b shows the trial deep drawing process of DX56D+Z which was predicted (Figure 6b) to exhibit better formability.

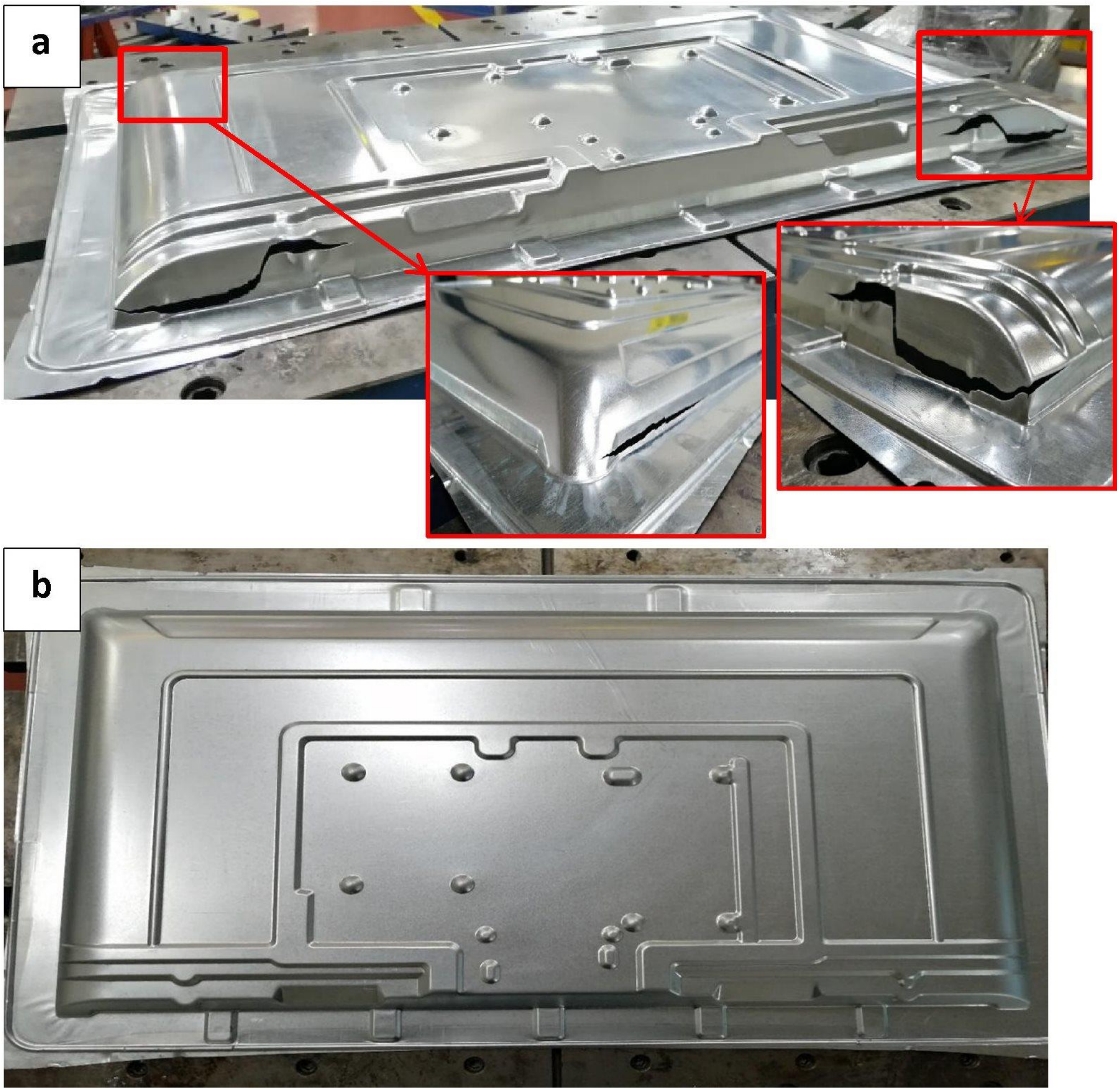


Figure 7. a) Tears encountered in deep drawing die output with drawbead of DX54D + Z sheet, b) Correct mold output from the deep drawing process of DX56D + Z sheet with drawbead

4.3. Optimization of Drawbead Geometry

Material flow must be regulated in certain regions in order to prevent or minimize defects in sheet material. Drawbeads are a kind of control mechanism that prevents material flow by braking in the required areas [25]. Thanks to this mechanism, defects in products can be prevented. DX56D+Z sheet material exhibited better formability according to simulations and trial production. Hence, optimization of the drawbead geometry and position was carried out for DX56D+Z. This also helps us to optimize the effect of tension force on product and pressure force of blank holders. Formability data of DX56D+Z for three different drawbead positions are given in Figure 8. According to Figure 8, if the DX56D + Z material is offset by 15 mm from the cutting line, its 82.60% area is shaped in full compliance with the form. However, in the 1.39% area, there is a tear above the forming limit curve. There was a risk of thinning in 0.29% area and tearing risk in 0.96% area. If the offset is adjusted above 20 mm, more than 87% area can be shaped in full compliance with the form. The risks of thinning, and tearing can be also reduced by offsetting 20-25 mm from the trimming line. Very close values were obtained when DX56D + Z material was offset 20 mm and 25 mm from the cutting line line. It has been decided that the drawbead should be within these optimum ranges.

Formability data obtained from Autoform for five different drawbead geometries were given in Table 3. It was noticed that the drawbead height affects the formability more than the drawbead radius.

Increasing drawbead height increased the tension force of the drawbead, hence it led to an increase in the areas of tearing, over thinning and risk [19]. Maximum safe area was obtained when the drawbead radius is 3 mm and drawbead height is 4 mm (R3/H4 mm). However, apart from the insufficient stress area for R3/H4 mm; tearing, the ratio of over thinning, thickening, crush and, risky areas of R3/H4 mm was found to be higher than that of R2.5/H3 mm (Table 3). Hence, optimum drawbead geometry was defined with a radius of 2.5 mm and height of 3 mm.

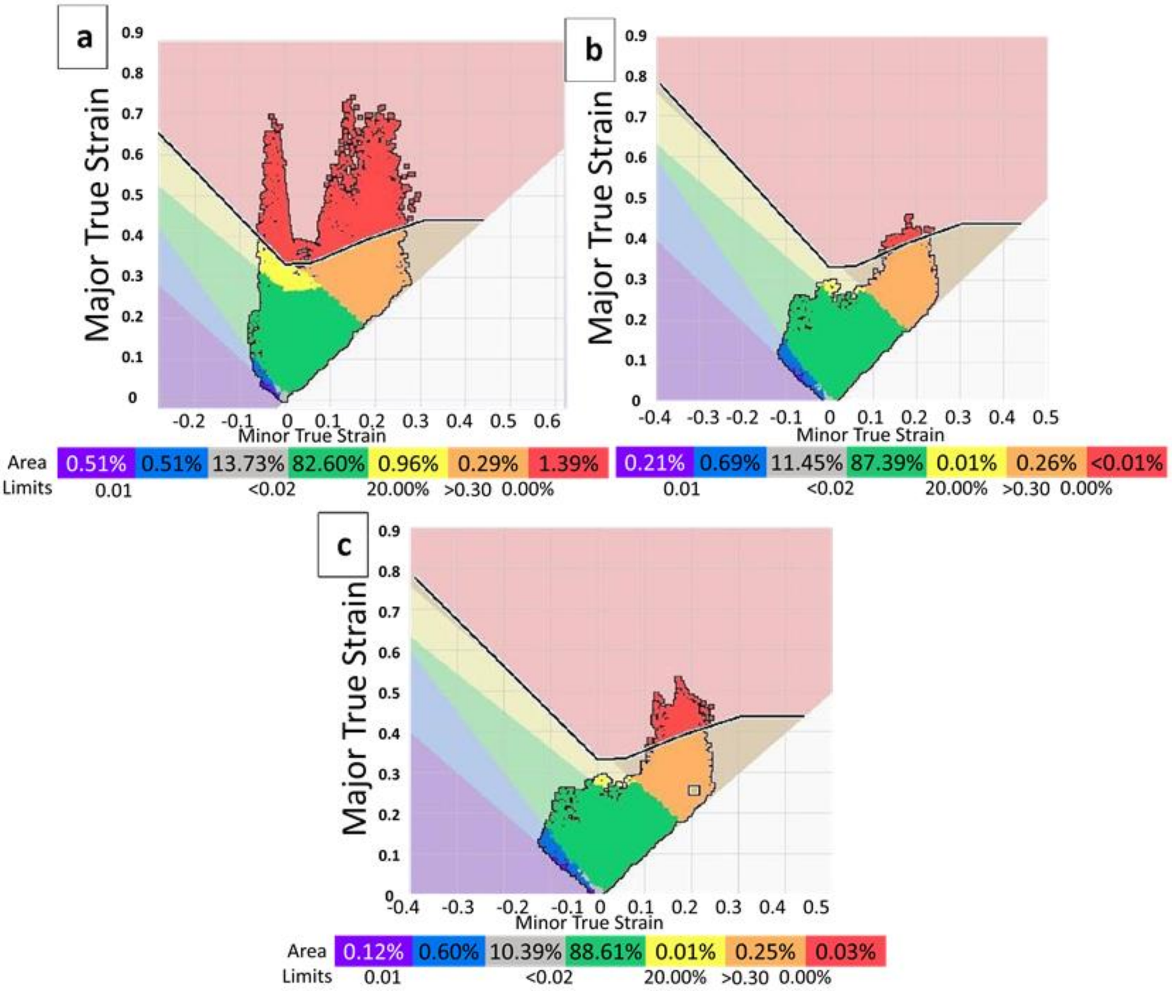


Figure 8. AutoForm formability representations according to drawbead positions (a) 15 mm (b) 20 mm (c) 25 mm offset FLD from the cutting line.

Tablo 3. Comparison of Formability Data According to drawbead geometry parameters

Material	R2.5/H3 mm	R2.5/H4 mm	R2.5/H5 mm	R3/H4 mm	R3/H5 mm
Thickening	0.12	0.87	1.38	0.62	1.29
Crush	0.19	0.4	0.36	0.47	0.37
Insufficient stress	10.55	8.91	11.04	8.52	8.43
Safe	88.79	88.7	83.83	89.61	87.69
Risky	0.08	0.44	1.38	0.32	0.99
Over thinning	0.27	0.32	0.34	0.31	0.28
Tearing	0.01	0.35	1.68	0.13	0.96

Figure 9 shows the trimming line, position of the drawbead, draw marks which arise from the drawbead tensile force and frictional force [6, 26], the amount of drawn material, and the distance between the trimming line and draw marks. In addition, a tie piece was added in order to optimize the deflection in the middle of the drawn part.

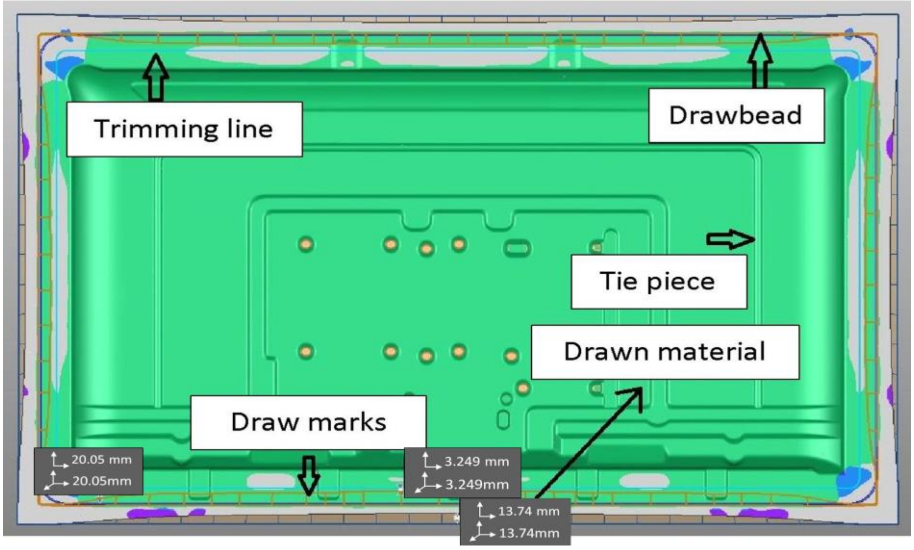


Figure 9. Display of trimming line and other parameters

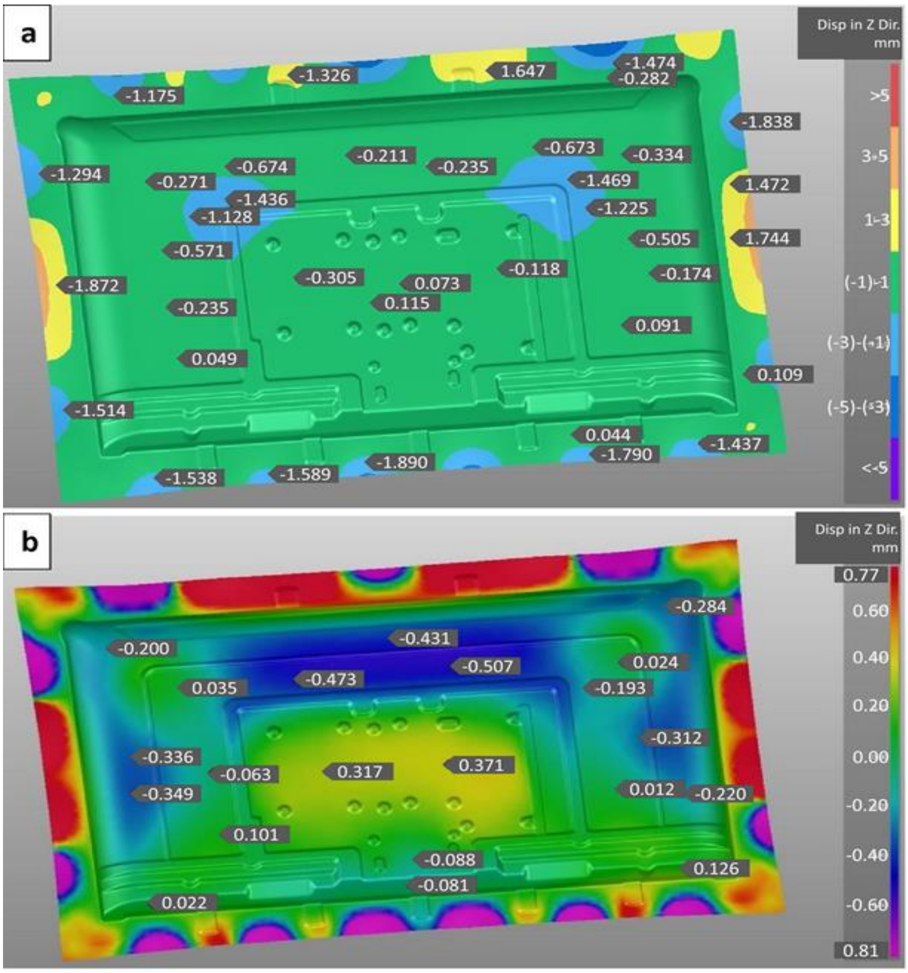


Figure 10. Displacement in the z-axis: a) without tie piece, b) with tie piece

4.4. Springback Simulations of DX56D+Z Steel Sheet

Springback is a frequently encountered problem in sheet metal forming which results in deviations from the net shape of the sheet metal [27-29]. For this reason, springback analysis is as important as the analyses done for the prediction of deep drawing problems and optimization. Springback analysis was carried out for DX56D+Z after determining the optimized drawbead geometry (Figure 10). First springback analysis was performed without the tie piece as shown in Figure 10a. In this case, displacement values in the z-axis got through to -1.5 mm which deteriorated the planarity around the middle of the simulated model. In order to overcome this excessive amount of displacement, a tie piece was added for supporting the deflected zone by increasing the tautening (Figure 10b). This modification reduced the displacement value in the z-axis from -1.5 mm approximately to -0.5 mm (Figure 10b).

5. Conclusions

This study simulated the formability of DX54D+Z and DX56D+Z steel sheets with deep drawing, and compared the Autoform simulations with the trail production of a given model. In addition, springback analysis and drawbead optimization studies were accomplished. The results can be summarized as follows;

1. DX56D+Z material exhibited better formability owing to its higher r-value (anisotropy) and low n value (strain hardening exponent). Deep drawing simulations by Autoform exhibited a good compatibility with the trial deep drawing process of both materials. DX54D+Z steel sheet experienced tearing after the deep drawing process as predicted by Autoform analysis. Autoform analysis based on FE was found to be beneficial to reduce the necessity of trial and error loop, accordingly it would reduce the production costs.
2. Simulations and trial production without a drawbead resulted in wrinkling, crush, and tearing of sheet metal. With an optimized drawbead geometry and position, deep drawing failures were reduced.
3. Springback analysis of deep drawn DX56D+Z steel sheet revealed a deflection in the middle of the model, hence it showed the necessity for a tie piece in order to increase the stiffness of the model to be produced. Springback analysis after the addition of a tie piece decreased the deflection of the model.

Acknowledgment

The authors thank Scientific Research Project Office of Manisa Celal Bayar University for the financial support with the project number of “2019-001” and Metalsan Endüstriyel Ürünler San. ve Tic. A.Ş. for their technical support.

Author(s) Contributions

HD and GG designed the this study. GG carried out analyzes for the solution by Autoform programme of the problems that occurred. HD and GG carried out the theoretical calculations together, wrote the results, and then wrote the article together with NÇ and CG, who received support.

All four authors read and approved the final version of the article.

Conflict of Interest

The authors declare that there is no conflict of interest.

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