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Investigation of material models on deep drawing and ironing processes

Derin çekme ve ütüleme proseslerinde malzeme modellerinin incelenmesi

Cihangir Kaplan[1,*], Cem Güleç[2], Mesut Arıkoğlu[3], Serkan Toros[4], Habip Gökay Korkmaz[5]

[1,2,3] Kentpar Automotive, Research and Development Center, 42100, Konya, Turkey
[4,5] Niğde Ömer Halisdemir University, Mechanical Engineering Department, 51240, Niğde, Turkey

Abstract

Within the scope of this study, the effects of yield and hardening criteria used in forming simulations on part geometric dimensions were investigated. As material 0.8 mm thick DC04 material is used. In the study, the results were compared using the Hill-48 and Barlat-91 yield criteria and experimental flow curve, Hockett-Sherby, Ludwig and Hollomon flow curve models. The studies were carried out in Simufact Sheet Metal Form software. Although all the models studied because of dimensional evaluations estimated within tolerance values, the model in which the experimental data were used with Hill-48 gave the closest results to the nominal dimensions.

Keywords: Sheet metal forming, Yield criteria, Deep drawing, Ironing

Öz

Bu çalışma kapsamında, şekillendirme simülasyonlarında kullanılan akma ve pekleşme kriterlerinin parça geometrik boyutlarına etkisi incelenmiştir. Malzeme olarak 0.8 mm kalınlığındaki DC04 malzemesi kullanılmıştır. Çalışmada Hill-48 ve Barlat-91 akma kriterleri ile deneysel akma eğrisi, Hockett-Sherby, Ludwig ve Hollomon akma eğrisi modelleri kullanılarak sonuçlar karşılaştırılmıştır. Çalışmalar Simufact Sheet Metal Form yazılımda gerçekleştirilmiştir. Boyutsal değerlendirmeler neticesinde çalışılan bütün modeller her ne kadar tolerans değerleri içerisinde tahmin etmiş olsa da deneysel verilerinin Hill-48 ile kullanıldığı model nominal boyutlara en yakın sonuçları vermiştir.

Anahtar kelimeler: Sac metal şekillendirme, Akma kriterleri, Derin çekme, Ütüleme

1 Introduction

In sheet metal forming processes, deep drawing, blanking and ironing are the most commonly used production technologies for mass production [1, 2]. Due to its short lead time and optimum cost efficiency, it is one of the first technologies that is the reference of mass production markets in the white goods and automotive industries [3].

The concept of material formability is important when talking about sheet metal forming, as it limits how deformable the material can be. Formability is defined as the ability of sheet metal to deform into a desired form without local necking or fracture. Formability depends on several factors such as material properties or process parameters strain paths, strain rate, temperature, etc.

By using various processes such as punching-blanking, bending, deep drawing and other methods with sheet metal die, it is possible to obtain aesthetic parts with both mechanical properties and visuals requested by the customer, within the tolerances specified in the technical drawing, even in the one millionth printing. Each process has some parameters that define the quality of the work obtained [4, 5].

The ability of a sheet metal to be forming without the mentioned defects is called formability. The forming surfaces of the die tools should be developed in such a way that they can make the product form error-free. In this context, the formability of the material should be analyzed in terms of process parameters. The first die surfaces developed in the CAD environment are updated as a result of examining the ability of materials to take form and the effect of process parameters on this form by using finite element analysis, and this process is provided iteratively. Each iteration step represents a finite element analysis or optimization step [6, 7]. Sheet metal forming simulations have high non-linearity due to large deformations and the presence of contact faces.

Finite element analysis is used for formability while developing components to be produced by sheet metal forming [8]. The use of numerical simulation has become critical in recent years as a way to optimize tool forming by predicting the outcome of the forming process. This provides significant reductions in trial time and effort [9].

The plastic forming method aims to obtain a permanent form by forcing a material to deform with a load above its yield stress. Sheet metal forming needs two equipments, press and die, for deep drawing, blanking and spinning processes [10]. With the application of pressure on the male (punch) and female tool bodies (dies), material flows die cavity and this forming step is called sheet metal forming [11]. A schematic outline of the sheet metal forming die system is shown in Figure 1.

Blanking is the separation process of the raw material in accordance with the desired size and geometry. The blanking

* Sorumlu yazar / Corresponding author, e-posta / e-mail: kaplancihangir@gmail.com (C. Kaplan)
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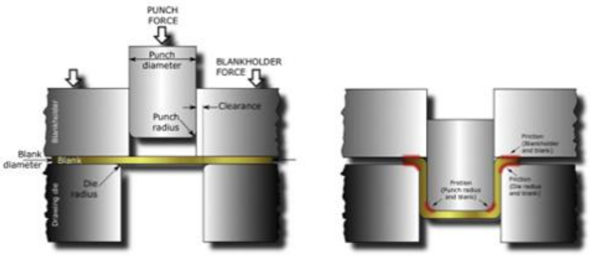


Figure 1. Schematic sheet metal forming setup [12]

process starts with the contact of the punch with the material. At first, fractures occur at both the upper and lower points. With further advancement of the punch, the elastic limit of the material is exceeded, and the material undergoes plastic deformation. These events occur in the first phase of blanking process. A force or predetermined motion is applied to the punch that causes it to move downward. In some press setups, the punch is fixed and the cavity of the dies is moved towards the punch. The blank contacts the punch and deformation of the blank is initiated. For this to happen, the sample must be restricted from moving in the same direction as the punch obtained by the spacer.

In this study, the deep drawing and ironing processes of DC04 EN 10130 sheet material, which is widely used in the manufacturing industry, were examined according to different the yield and hardening criteria. In the analysis studies, the dimensional geometric dimensions of the determined model and sheet metal sample were examined.

2 Material and method

DC04 EN10130 sheet material, which is in high demand in the manufacturing industry, is a cold rolling product and is frequently used in the automotive industry and in the white goods industry. The chemical components of DC04 EN10130 material forming in die designed for the scope of the study are given in Table 1. It has significant advantages in the forming ability of the material, the main alloying element of which is C.

Table 1. Chemical composition of DC04 EN10130 cold rolled steel (wt%)

C	Si	Mn	P	S	Cr	Ni	Cu
0.007	0.006	0.138	0.003	0.009	0.037	0.03	0.073

The stress strain curve is one of the important data used to investigate the mechanical properties of a material. Finite element analyzes play an important role in sheet metal forming processes and in the evaluation of results. In finite element analysis, the true stress-strain curve of the sheet material is generally preferred as the input parameter. It is necessary to obtain the yield curve of the material, especially in forming processes where the sheet is exposed to large deformations. The stress-strain curve of a sheet is usually obtained from the tensile test. It is not easy to obtain the curve for large strains after tensile strength. Even the strain corresponding to the tensile strength has lost its ability to describe the material property [5].

One of the main factors affecting the geometric tolerances of the product is the material properties. Therefore, it is necessary to determine the mechanical properties of the material. Tensile tests are performed for the mechanical properties of the material such as yield stress, tensile stress, elastic modulus, poisson's ratio. Samples were prepared from DC04 EN 10130 cold rolled material, which will be used in the process, by determining the dimensions in accordance with ASTM E8 standard. Sample dimensions of the ASTM E8 standard are shown in Figure 2.

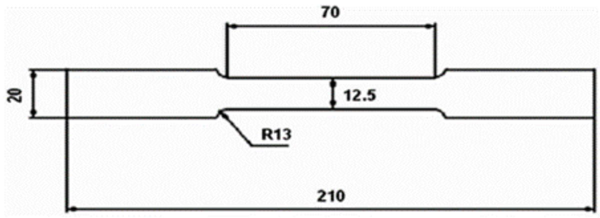


Figure 2. Sample sizes in accordance with ASTM E8 standard [13]

To determine the yield, tensile and fracture stresses of the material with tensile tests, the stress-strain curve must be plotted. In Figure 3, the flow curve of 0.8 mm thick DC04 EN 10130 sheet material obtained at a strain rate of $0.00833 s^{-1}$ (25 mm/min) is shown. One of the essential material properties in the sheet forming is the Lankford parameters which are required to calculate the coefficients of the anisotropic yield criteria.

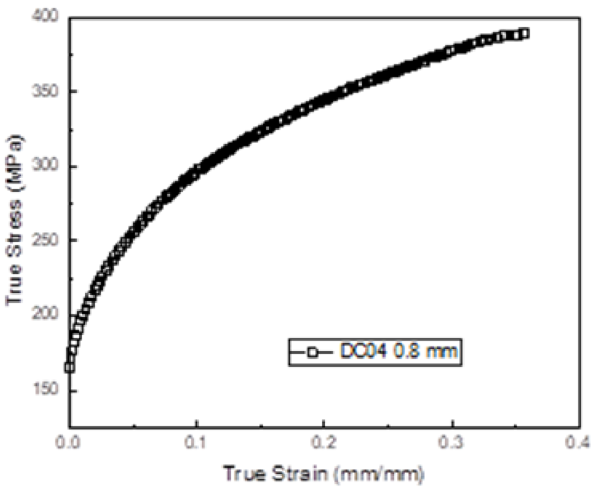


Figure 3. Flow curve of 0.8 mm DC04 EN10130

Table 2. Mechanical properties of DC04 EN10130 cold rolled steel

Mechanical Property	Value
Young' modulus (MPa)	180000
Poisson' ratio	0.283
Density (kg/m^3)	7851
Tensile strenght (MPa)	388
R_0/σ_0	1.85/166
R_{45}/σ_{45}	1.25/175
R_{90}/σ_{90}	2.25/170

Mechanical properties of DC04 EN 10130 sheet material are given in Table 2 to create a model for Simufact Sheet Metal Forming analysis. In the related model, yield strengths of the material in three different directions (0,45,90) and Lankford parameters are defined.

2.1 Material models

Within the scope of the study, some of the flow curve models in the material property section of the Simufact Sheet Metal Forming software were used and their performances in the forming simulations were compared. First, flow curve modeling of DC04 material was performed and experimental flow curve, Hockett-Sherby, Ludwig and Hollomon equations were used.

The equation of the Hockett-Sherby model is expressed as follows.

$$\sigma_F = b - (b - a).e^{-m.\varphi^n} \tag{1}$$

Here, σ_F is the stress, a yield stress, n is the material parameter, m is the material, and φ is the strain.

The equation of the Ludwig model is expressed as follows.

$$\sigma_F = A + C.\varphi^N \tag{2}$$

Here, σ_F stress, A yield stress, C strength efficient, N hardening exp., φ strain values.

The equation of the Cold Forging Metal Form-2 (Hollomon Eq.) model was used. The equation is given below.

$$\sigma_F = C.\varphi^N \tag{3}$$

Here, σ_F is stress, C is strength efficient, N is hardening exp., φ is strain.

Another important model used in the simulations of sheet metal forming processes is yield surface models. The yield surface models are the models that determine the plastic deformation of the material under multiaxial stresses that occur in multiaxial forming conditions. Although there are many studies in this field in the simulations, analyzes were carried out with reference to two anisotropic yield criteria in Simufact Software within the scope of this study. These anisotropic yield surfaces are Hill-48 and Barlat-91, respectively. The equations of the relevant models are given below. Another important model used in the simulations of sheet metal forming processes is yield surface models. The yield surface models are the models that determine the plastic deformation of the material under multiaxial stresses that occur in multiaxial forming conditions. Although there are many studies in this field in the simulations, analyzes were carried out with reference to two anisotropic yield criteria in Simufact software within the scope of this study. These anisotropic yield surfaces are Hill-48 and Barlat-91, respectively. The equations of the relevant models are given below.

In the simulations, Hill-48 anisotropic yield criterion is used forming processes, and the criterion is given in Equation 4 as a quadratic function [14]

$$2f(\sigma_{ij}) \equiv F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + H(\sigma_x - \sigma_y)^2 + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \tag{4}$$

Here, f is the yield function, F, G, H, L, M, N are the anisotropic parameters of the material and x, y, z are the principal anisotropic axes. In the case where the principal axes of the stress tensor coincide with the anisotropic axes ($\sigma_x = \sigma_1$, $\sigma_y = \sigma_2$, $\tau_{xy}=0$), the Hill-48 yield criterion is given in Equation 5 depending on the principal stresses and Lankford coefficients [15].

$$(\sigma_1^2) - \frac{2r_0}{1+r_0}\sigma_1\sigma_2 + \frac{r_0(1+r_{90})}{r_{90}(1+r_0)}\sigma_2^2 = \frac{r_0(1+r_{90})}{r_{90}(1+r_0)}r_{90}^2 \tag{5}$$

In order to establish the plasticity model, the yield criterion, flow rule and hardening rule must be defined. The yield criterion defines the elastic limit in the stress space, the flow rule determines the direction of the plastic strain increment, and the hardening rule defines the evolution of the yield surface. In this study, the yield criterion Yld91 was used for the definition of the initial anisotropy of the material and Yld91 is a six-component yield criterion. It was developed by Barlat [16]. This criterion is based on the linear transformation approach and is expressed as follows:

$$|S_1 - S_2|^m + |S_2 - S_3|^m + |S_3 - S_1|^m = 2\bar{\sigma}^m \tag{6}$$

$$S = \begin{bmatrix} \frac{C_3(\sigma_{xx}-\sigma_{yy}) - C_2(\sigma_{zz}-\sigma_{xx})}{3} & C_6\sigma_{xy} & C_5\sigma_{zx} \\ C_6\sigma_{xy} & \frac{C_1(\sigma_{yy}-\sigma_{zz}) - C_3(\sigma_{xx}-\sigma_{yy})}{3} & C_4\sigma_{zy} \\ C_5\sigma_{zx} & C_4\sigma_{zy} & \frac{C_2(\sigma_{zz}-\sigma_{xx}) - C_3(\sigma_{yy}-\sigma_{zz})}{3} \end{bmatrix} \tag{7}$$

Where σ is the effective stress, S_1, S_2 and S_3 are the principal values of deviatoric stress tensor.

3 Process simulations

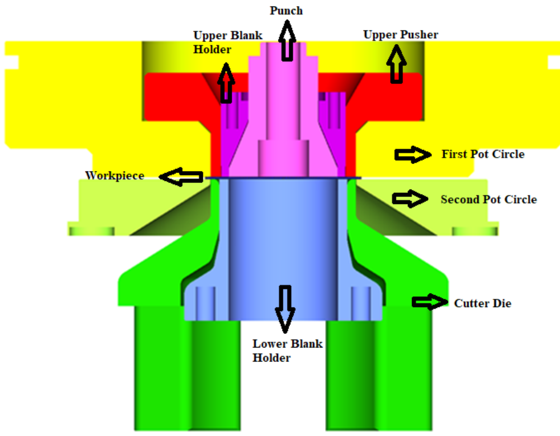


Figure 4. Forming die system view

The simulations of the blanking and spinning operations were carried out using the Sheet Metal Foming Module of the Simufact software. The tools in the system are assumed to be rigid. The surface interactions of the die elements and the sheet material are modeled according to Coulomb's Law. According to this law, the friction coefficient value of 0.08 was used in the analysis. In the finite element analysis model, the temperatures of the sheet/workpiece and die parts were taken as 20 °C. Adiabatic heating due to plastic deformation and temperature increases due to friction and their effects on the mechanical behavior of the sheet material are ignored. The tear control of sheet material in blanking and spinning operations was carried out using the normalized Cockroft Latham ductile material ductile fracture model, and the relevant model is given in Equation 8. In the equation, σ_{max} is the calculated maximum stress on the sheets and the σ_{eff} is the equivalent stress. In addition, ε_{eff}^{pl} effective plastic strain and C is the critical damage factor which can be calibrated according to the failure strain f the materials during the given deformations.

$$\int_0^{\varepsilon_f} \frac{\sigma_{max}}{\sigma_{eff}} . \varepsilon_{eff}^{pl} \mathrm{dt} \geq \mathrm{C} \tag{8}$$

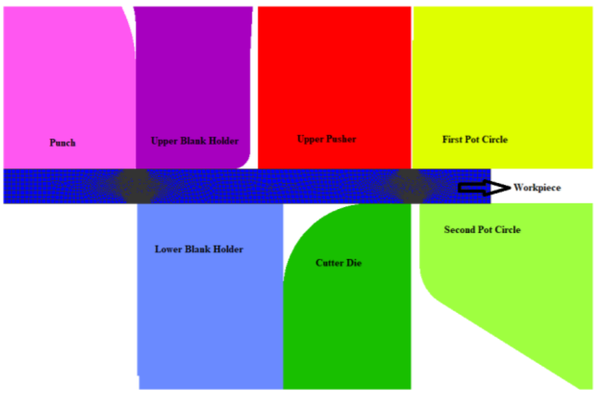
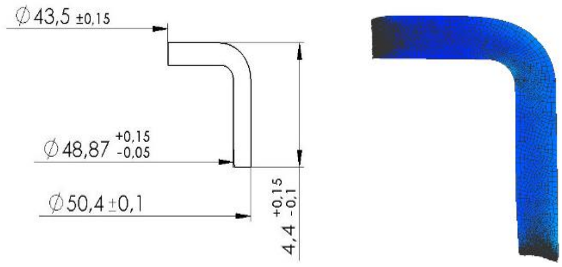


Figure 5. Workpiece mesh structure view

In Figure 5, the mesh structure of the workpiece, which was analyzed in the blanking and ironing die system, is shown. The mesh type of the workpiece was determined as Advancing Front Quad, and the element type was quadratic shell element. In this way, the workpiece has the number of elements 13488. Adaptivite mesh has been added to the surfaces where blanking will be made. Thus, a denser mesh structure was provided in that region. It is aimed that the data to be obtained at the time of blanking and ironing is correct.

4 Results and discussion

In this study, numerical analyses were performed using Simufact Sheet Metal Forming finite element software for the blanking, drawing and ironing operations. The automotive sheet metal spare part to be produced is shown in Figure 6. The appropriate yield and flow curve models were determined according to the prediction performance of geometrical dimensions with their tolerances for the specific regions of the formed part. In addition to forming operations, the springback evaluation was also carried out for the selected part. As can be seen from Figure 6(b) the burr formation was also visualized and the dimensions were measured from the peak edge of the bottom and the flat side of the top of thee formed part.



(a) (b)

Figure 6. Technical drawing and analysis results

Experimental Flow Curve Table, Hockett-Sherby, Ludwig and Hollomon models can be found in Simufact Sheet Metal Forming Software to define the stress strain relation of the materials. Analyzes were carried out according to these models. The models' fitting performances were illustrated in Figure 8. As can be seen from the figure, although the fitting performance shows good agreement with the experimental curve, extrapolated data of the model shows difference with the experimental data. These values are very important in the view of the calculation of the stresses for the propagate strain levels. Therefore, these differences affect the results of simulations particularly springback and failure predictions.

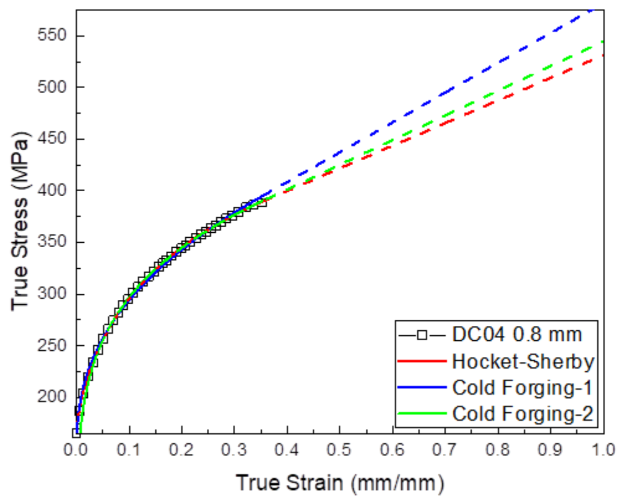


Figure 7. Tables flow curve model

After the graphics which is determined by regression model, (Figure 7) were created the model parameters of the equations of Hockett-Sherby, Ludwig and Hollomon models are given in the Table 3-4, respectively.

Eight analyzes were carried out by establishing models according to the yield and hardening criteria using the finite element software. The comparison of the sheet metal part to be produced according to the analysis results to the technical

Table 3. Hockett-Sherby equation value

Equation	Value
b	162.61
a	497.75
m	2.19
n	0.63
r-square	0.999

Table 4. Ludwig equation value

Equation	Value
A	162.61
C	497.75
N	2.19
r-square	0.997

Table 5. Hollomon equation value

Equation	Value
A	489.27
N	0.21
r-square	0.975

drawing dimensions is shown in Figures 9, 10, 11 and 12. As shown in the graphics, the Hill-48 model, which was prepared according to the experimental data, estimated 98.9% on average in the part length, hole diameter, inner and outer diameters. It is at a satisfactory level for the cases examined.

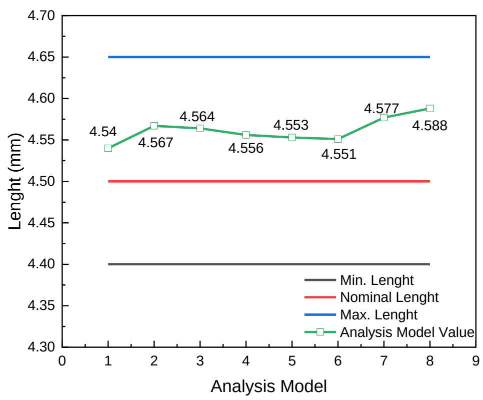


Figure 8. Part length results according to analysis models

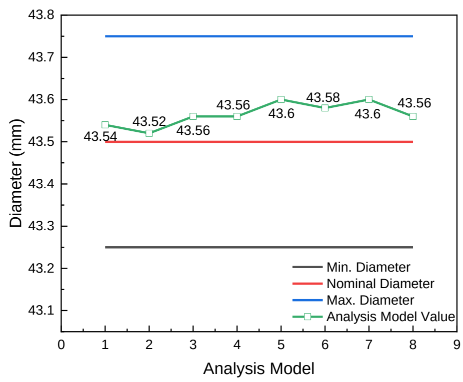


Figure 9. Hole diameter results according to analysis models

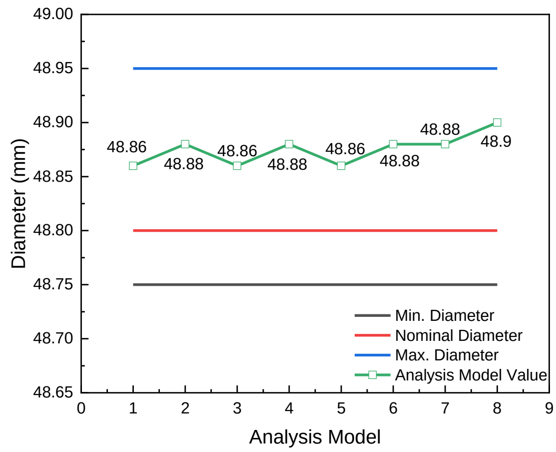


Figure 10. Inner diameter results according to analysis models

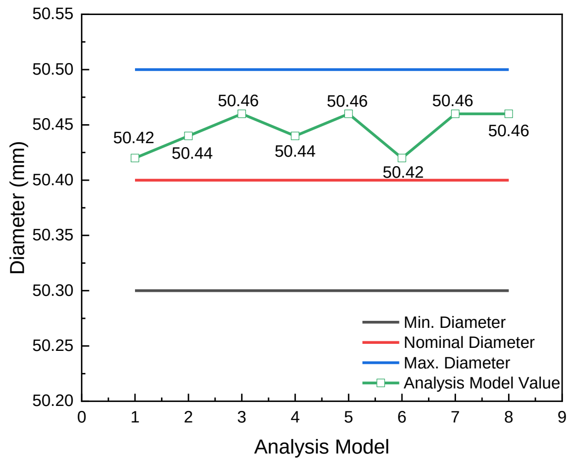


Figure 11. Outer diameter results according to analysis models

5 Conclusion

In this study, the material model performances that are used in the such a complex forming simulations are evaluated. As a flow curve model Table of Experimental Data, Hockett-Sherby, Ludwig and Hollomon model were used. Besides that, Hill-48 and Barlat 91 yield criteria were used, and the results were compared. According to simulation results of the processes Hill-48 anisotropic yield criteria with the experimental flow curve has the best predictions in the view of the dimensional tolerances. As shown in the graphs, it was estimated at 99.11% in part length, 99.11% in hole diameter, 98.75% in inner diameter and 99.96% in outer diameter. It is at a satisfactory level for the cases examined.

Conflicts of interest

No conflict of interest was declared by the authors.

Similarity rate (iThenticate): 9%

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