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Original Article

Analysis of the Fatigue Life of Matrix Elements in the Hole Drilling Process in Sheet Metal Forming Dies

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Abstract - *Sheet metal forming die technologies show great progress in the industry daily. Sheet metal dies design depends on many parameters, such as the product's geometry, the die dimensions to be designed, the number of products, and part operation. The main purpose of the designs is to design the die with optimum parameters and to obtain high-quality products. One of the reasons for these errors is the damage to the die elements during operation. This study analyzed the final process of sheet metal forming dies using a progressive two-axis in-die conveying system designed with Catia V5 software. The lifetime analysis of the matrix element used in the hole drilling process was made with Ansys software, in which the finite element method was applied. The analysis compared two materials used in die design, AISI D2 and AISI A2 tool steels. The effects of matrix thickness on fatigue life were analyzed separately for matrices with 8 mm, 10 mm, and 12 mm thicknesses. According to the analysis results, it was concluded that the longest fatigue life is in the dies with a 12 mm thick matrix in which AISI D2 steel material is used.*

Keywords - *Sheet metal forming, Drilling process, Fatigue analysis.*

1. Introduction

Sheet metal forming processes are widely used in automotive, white goods, electronics, and many industries. It is desired to increase efficiency by enabling the sheet-forming dies used in mass production to produce more in a shorter time. Progressive and transfer die are used to ensure competition and to combine different operations for a single piece. These dies perform multiple operations sequentially, without the need for manual handling, with faster and higher quality PLC systems[1].On the other hand, transfer dies to hold many processes together, employing plates that make them common. In transfer dies, in-die transports are carried manually or by a carrier arm mechanism [2].

Sheet metal forming dies consist of three main parts: lower die, upper die, and sheet to be shaped. Dies are designed using computer-aided drawing programs such as Catia V5, Solidworks, and AutoCAD. CAD data of the designed dies can be analyzed with simulation programs. The finite element method analyzes sheet metal formability and cutting feasibility before production [3]. The analysis not only evaluates the forming process but also provides an idea about the live performance of the dies. It is important to carry out this analysis before the dies are damaged under repeated loads [4]. Fatigue analysis, on the other hand, shows the relationship between the number of stress cycles and the shape limit, and the curve is called a Wöhler curve or S-N curve [5, 6]. The fatigue life of the die, the product being formed, die design, production method, die material strength, and the entire forming process [7]. One of the prominent factors in sheet metal forming dies is the estimation of tool fatigue life [8]. İt is because if the die suffers sudden fatigue damage, die elements can be damaged, and undesirable errors such as wrinkling, tearing, and crushing the sheet metal may occur. Fatigue failures show themselves not only with fracture and crack formation but also with wear behavior. These errors interrupt the production process of the die and cause a loss of time during repair or replacement [9]. The estimation of the working life of the mold can be made by experimental analysis and numerical modeling. While experimental analyses successfully ensure a defect-free production process, they are generally more expensive and take a longer time[10]. Fatigue analysis is performed with software programs such as Ansys to estimate the working life of the die. However, in sheet metal forming processes, Incomplete or incorrect creation of data such as material flow, ignoring the stress distribution, insufficient input of the process parameters, and the mesh structure is also given to the die elements for the simulation program affects the fatigue analysis results [11]. For this reason, the analysis provides to obtain approximate values.

Studies in the literature on die design are extremely limited. Using Li et al.'s Ansys/Ls-Dyna program, they analyzed the punching pattern with the "Explicit Dynamics" module. In the simulations, different surface treatments applied to the punches were investigated. According to the analysis results, the fatigue strength of the parts subjected to fatigue depends on the material selection, production method, and design parameters. The analysis results emphasized the importance of surface treatments for improving the die [12]. In the notching process, stresses occur on the punch due to the steel's high strength and the sheet's thickness. Lee et al. predicted the punch's wear and fatigue behavior by analyzing and verifying it with experiments.

Drilling operations were analyzed using DEFORM 2D. DEFORM 3D is also used in retainer forming processes. As a result of the study, it was concluded that the wear life is longer than the fatigue life. Fatigue life is a criterion for the notch punch change period[13]. In their study, Fu et al. developed a method to improve the fatigue life of the designed sheet metal forming dies most efficiently. For this method, firstly, the simulation of the material flow to the die and its deformation during the forming process are defined. The most appropriate design was determined with the determined case study. In this way, the developed method was validated [7]. When the die is designed optimally, it also positively affects the die's life. Tong et al., in their study, stated that the die life is determined by the stress state of the die material, even though the process steps are designed to be the most efficient. The die configuration designed with CAD software was transferred to the CAE platform, and the maximum-minimum principal stresses on the female die surface were determined by finite element analysis. The places with the highest stresses were estimated as the places with the greatest fatigue damage, and the fatigue life was investigated [14]. Naranje et al. conducted a study using artificial neural networks to estimate fatigue failures in dies without die damage. In their study, they used the stress amplitude (S) and looped up to error the detection (N) approach to estimate the number of cycles in deep drawing dies [15]. Ford-Otosan company analyzed the life of the old die of the middle roof panel of the Jumbo vehicle model.

The die was designed with the Pro/Engineer program and analyzed in Ansys/Workbench environment. These analyzes were made according to the Goodman, Soderberg, Gerber, and Mean-Stress Curve options. The results show that the die is safe against loading [8]. When the studies on this subject were examined, it was seen that fatigue analysis was carried out not only in sheet metal dies but also in many parts in the automotive sector [5, 16, 17, 18]. Many studies were found on fatigue analysis of shaped sheet metals. However, fatigue analysis of sheet metal forming dies is more limited. For this reason, fatigue analysis of the hole drilling operation was made for the transfer die produced.

In this study, matrix (female die) fatigue analysis was carried out for the drilling operation of the progressive two-axis transport system transfer die used during the production of an automobile part in the automotive supply industry. In the study, the female die (matrix) was analyzed for the hole-drilling process, which is the last process of the die. In the analysis, different matrix thicknesses and two different materials were examined. The variation of fatigue analysis results with different designs was compared according to life and safety factor values.

2. Material and Method

The interconnection bracket, which acts as a cover in the bumper bracket in the automotive industry, is produced from DP600 sheet material by sheet metal forming methods. To increase the annual production numbers and increase the production efficiency, it is aimed to manufacture the part produced in 2 separate dies in a single die. For this reason, a die design with a progressive biaxial in-die transport system has been made. New production processes for the designed die were carried out in Autoform finite element software for sheet material. In these analyses, it has been concluded that the sheet material can successfully be brought to its final shape. Ansys 2019 R2 software was used to analyze the die elements to be produced. For the drilling process supported by the cam system, which is the die's last operation, the matrices' lifetime analysis has been made. AISI A2 and AISI D2 steels, widely used as die steel and have S-N curves in Ansys 2019 R2 software, were selected. The thickness of the matrix that meets the punch force in the hole punching process, the thickness values for the finite element analysis study, 8mm, 10mm, and 12mm, were determined, and tests were carried out for all thickness values with 2 different materials selected.

2.1. Die Design with Progressive Bi-Axis In-Die Transport System

In the die design first of all, the die design was made to produce the interconnection bracket, which acts as a casing in the bumper bracket. Working principles of progressive and transfer die mechanisms are brought together for the die design of the part. Before the designed die, the opening cutting process is carried out in one die, and the bending 1st operation, bending 2nd operation, and punching operation are performed in another die. After the design work, these 4 operations were put into production in a progressive biaxial in-die transport die. With this new die, the number of presses used during production has been reduced from 2 to 1. Transport between presses is also eliminated. The interconnection bracket, which has a production time of 16.33 seconds with 2 dies, can be produced in 6 seconds with the new die design. With this developed die system, production time and quality have increased, and the results have been reflected as an increase in productivity. The newly designed die is given in Figure 1.

The last operation of the interconnect bracket was determined as a drilling operation. Drilling process; It is the cutting process by combining the female die with the punching group in the press systems. The female die that assists the cutting process is also called the matrix.[19] Figure 2 shows the die elements of the drilling process in a 3D cross-sectional view.

2.2. Die Design Materials

In the die sector, research is carried out on cold work tool steels that provide longer life and ease of processing. Tool steels that are required to work under high forces; are also subjected to heat treatment to gain properties such as wear resistance, toughness, and fracture resistance under high forces.[20] In the sheet metal forming process, 1.2379 (AISI D2) steel, which is cold tool steel, is used as punch, matrix, and matrix retainer material.[21, 22, 23] These steels have high wear resistance and hardening safety.

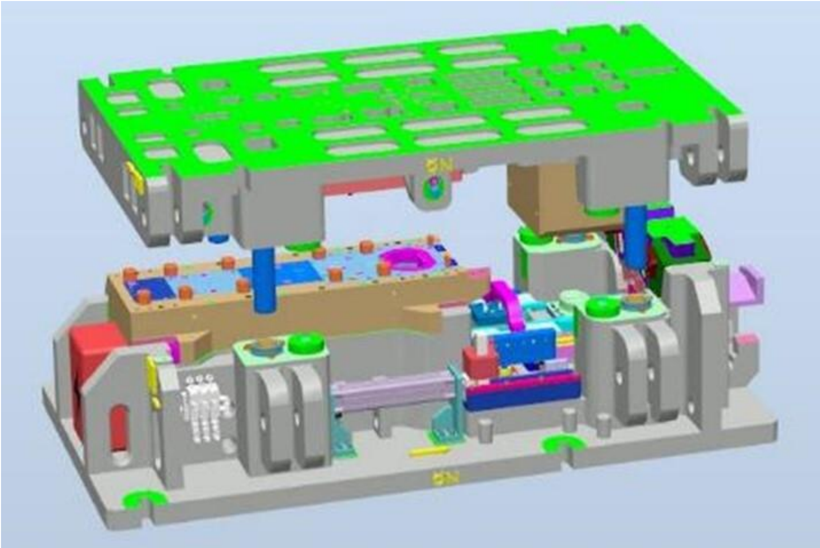

Fig. 1 CAD model of sheet metal forming die with progressive biaxial in-die conveying system

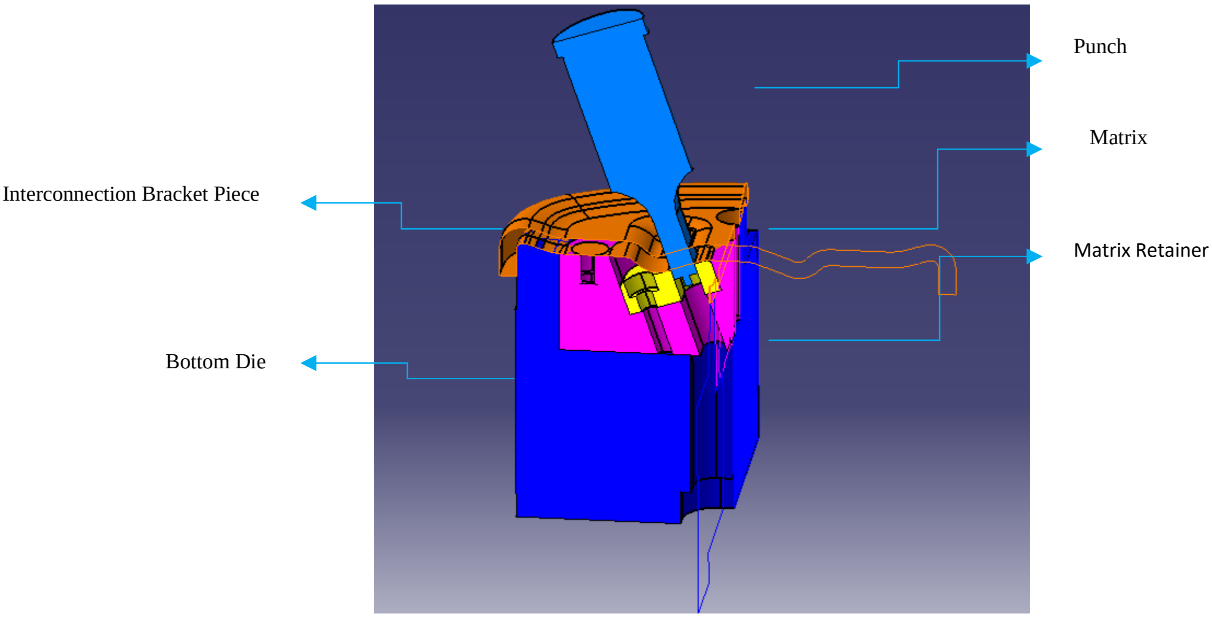

Fig. 2 Sectional view of the progressive die drilling process and process elements

1.2379 Cold tool steels are widely used due to current market conditions and suitability for production. For this reason, D2 steels can be easily obtained and processed in batches, and their costs are appropriate. Another tool steel used in dies is A-type steel. The AISI A2 steels used in the study are tool steels with similar properties to D2 steels but different from them, which are air-hardened. Two different tool steel analyses that can be used as tool steel in the progressive two-axis transport system transfer die were analyzed. When AISI D2 and A2 steels were compared in terms of material structure, it was seen in studies that D2 steel outperformed A2 steel.[24,25] One of the reasons for this is that D2 steel has a higher chromium content than A2 steel. The amount of chromium in the material structure increases the wear resistance.[25,26] The chemical composition of AISI D2 and AISI A2 materials is shown in Table 1. The mechanical properties of tool steels are given in Table 2.

Table 1. Chemical composition of AISI D2 and A2 tool steels

Material	Composition (% wt)					
	C	Mn	Si	Mo	Cr	V
D2	1.55	0.4	0.3	0.8	12	0.8
A2	1.0	0.6	0.3	1.10	5.5	0.2

Table 2. Mechanical properties of AISI D2 and AISI A2 steels

Material	Young's Modulus (MPa)	Tensile Strength (MPa)	Yield Strength (MPa)
D2	2,1 e5	2292	2066
A2	2,109 e5	2194	1962

In the study, AISI A2 and AISI D2 steels were selected for the analysis, and the results were evaluated by comparing the two materials.

2.3. Modeling of Drilling Operation and Finite Element Analysis and Results

In the punching operation, the matrix, the matrix retainer, and the punch are used for punching, which is the last operation of the interconnection bracket in the transfer die. For this process, the cutting force is calculated depending on the length of the sheet material to be cut, the yield strength, and the sum of the cutting circumference.

For the analysis, only the drilling operation of the progressive biaxial support arm die. The shear force on the matrix, the direction of the forces acting on the matrix during the drilling process, and the areas affected by these forces have been determined by experience and previous studies. Figure 3 shows the force acting on the matrix and its direction. In matrix dimensions, designing the die as small as possible and angled drilling are constraints. Since the area where the matrices will be placed is narrow, the increase in their size causes dies collision. For this reason, it is planned to study the matrix thickness between 8 mm and 12 mm.

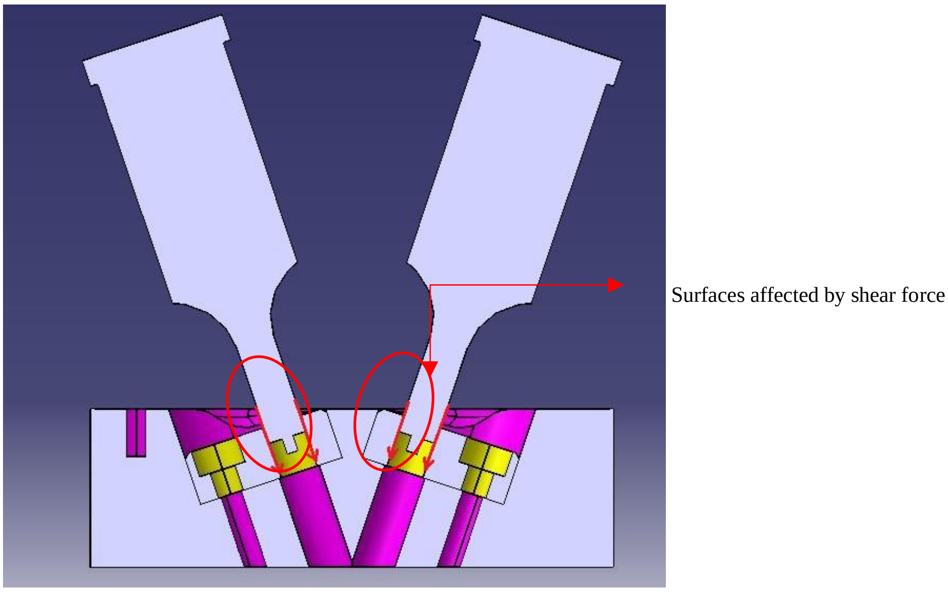

Fig. 3 Surfaces on which the applied shear force affects the matrix

Interconnection bracket obtained by forming process; DP600 is manufactured from sheet material. The chemical composition and mechanical properties of the DP600 commercial material are given in Tables 3 and 4, respectively.

For the analysis of matrices and matrix retainers under shear force, it was transferred to Ansys 2019 R2 finite element program. For static analysis, a connection is made between the die elements. The two parts are fixed to each other by giving a "bonded" connection between the matrix and the matrix retainer. Figure 4 shows the connection points.

The loading conditions of the elements with acceptable mesh quality were determined. The fixed subbase is given in Figure 5.

Table 3. Chemical properties of DP600 steel sheets (% wt)

Material	C	Mn	P	S	Si	Al	N	Cu+Cr+Ni
DP600	0.12	1.40	0.085	0.008	0.50	0.020-0.060	0.009	1.30

Table 4. Mechanical properties of DP600 steel sheets [27]

Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
DP600	400±20	630±20	23±2

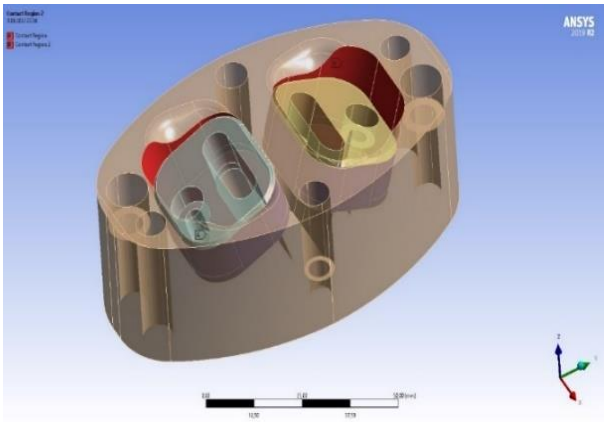

Fig. 4 Contact structure between matrices and matrix retainer

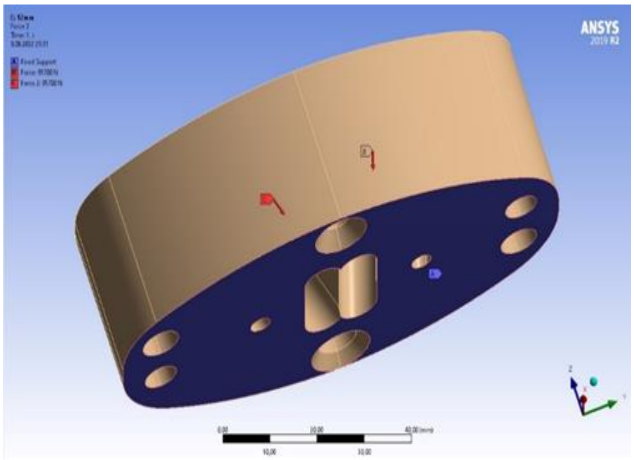

Fig. 5 Fixing surface with matrix retainer fixed support

The matrix retainer is fixed from its lower surface with "fixed support." As shown in Figure 6, a shear force was applied to the area where the punch would pierce the part and come into contact with the matrix, and "Von-Mises Stress-Total Deformation" analyzes were performed.

The friction force is not given to the surfaces that the punch will touch. İt is because when the friction value is high at the interfaces of the blank holder plate, and the bottom die, higher punch forces are required and cause the punch to break [28].

After giving the necessary relations for the static analysis, the behavior of the matrices under shear force was evaluated. Von-Mises stress values and total deformations were compared in the analysis.

The analysis results shown are evaluated as "All Bodies." As a result of the analysis, Von Mises Stress values of both materials for 8 mm and 12 mm thick matrices were equal and less than 10 mm. It was evaluated that these values were equal due to the close mesh structures and mechanical properties. The highest Von-Mises stress was determined in the matrix made of 10 mm thick D2 tool steel, which was designed and started to be used for mass production. When the analysis results were examined, it was concluded that the high-stress values were not on the matrix but on the lower surface of the matrix retainer. Figure 7 shows the Max Von-Mises value of the matrix designed from 10 mm thick D2 tool steel.

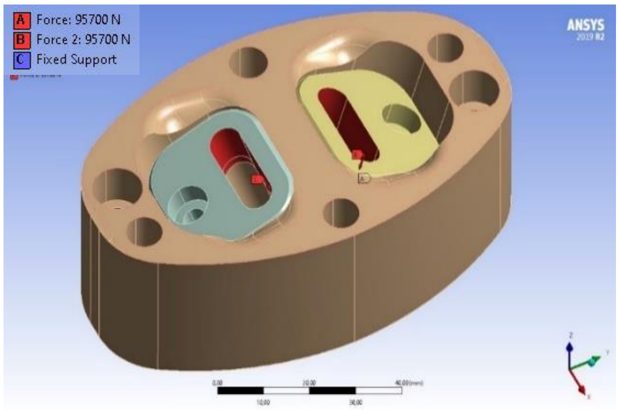

Fig. 6 The surfaces on which the force is applied to the matrix

In Von-Mises stress analysis, it was observed that other matrix designs also had critical yield values at similar points. The area where the piece cut by the drilling operation is dropped from the matrix retainer is considered critical.

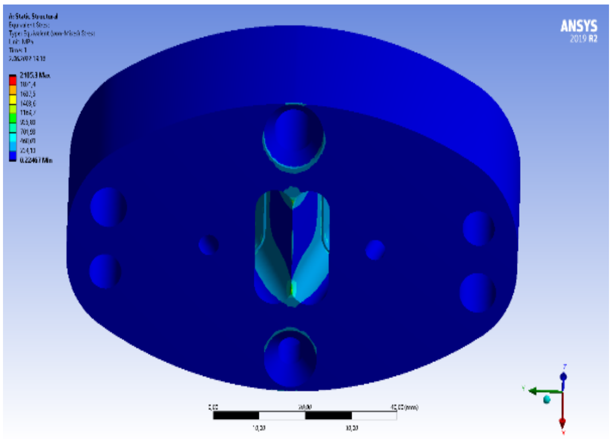

Fig. 7 10 mm thick D2 tool steel matrix surface

When the Von Mises stress values on the matrix were examined, it was concluded that it was well below the yield limit and that the matrices were not critical for 3 different thicknesses for 2 materials. For A2 tool steel, the highest Von Mises stresses of 8 mm, 10 mm, and 12 mm thick matrices are, respectively, 650.52 MPa, 468.07 MPa, and 490.4 MPa. The highest Von-Mises stresses of 8 mm, 10 mm, and 12 mm thick matrices for D2 tool steel; are 650.51 MPa, 468.3 MPa, and 490.4 MPa. It was concluded that the highest Von-Mises stress in the matrices is at the edges of the matrix.

3. Drilling Operation Matrix Fatigue Analysis

The study aims to examine the effect of cutting force on the fatigue life of the matrix (female die) in the sheet material cutting process. The interconnection bracket, which acts as a cover on the bumper bracket, has an annual production of 179,000. Therefore, the designed matrix is expected to withstand a minimum of 179.000 cycles. One of the constraints of the designed die is that it is designed for a narrow space. Three different matrix thicknesses were studied, depending on the constraints.

The suspension mount is a commercially available DP600 steel material. In the analysis of the fatigue behavior of the matrix, 3 different matrix thicknesses and 2 different tool sheets of steel were used. Tool steels were selected from the library of the finite element software. Wöhler graphs required for fatigue analysis are available in the literature. However, the experimental conditions of the studies vary.

Wöhler curves used for fatigue analysis are expressed as the number of cycles at which damage occurs for constant average stress. These curves are also called S-N curves. For this reason, S-N graphs of tool steels in the Ansys material library were used in the fatigue analysis.

Fatigue analyses with the finite element method do not give the same results as fatigue analyses under real operating conditions. The most important reason for this is the parameters affecting the study. This study's strength value expressed by "S" was accepted as 0.9 for matrix fatigue analysis. After the mentioned assumptions were made, fatigue analysis was studied. Fatigue life analyzes are shown in Figure 8, and the life values obtained as a result of the analysis are shown in Table 5.

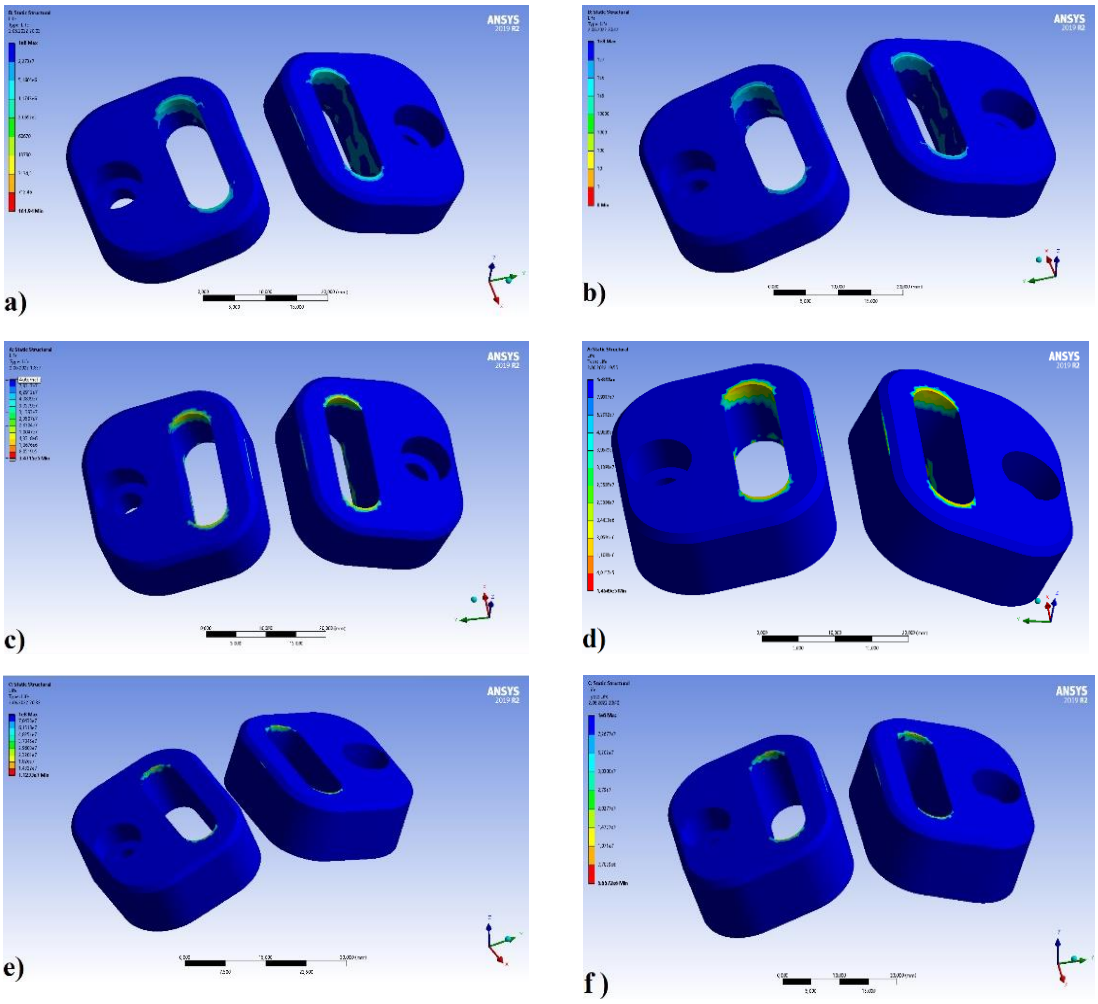

Fig. 8 Fatigue analysis of matrices under shear force, (a) 8 mm D2 tool steel, (b) 8 mm A2 tool steel, (c) 10 mm D2 tool steel, (d) 10 mm, A2 tool steel, (e) 12 mm, D2 tool (f) 12mm A2 tool steel

Analysis results are given in Table 5. According to the numerically expressed values, the 12 mm thick matrix made of D2 steel has the longest cycle time. On the other hand, operating A2 steel with a thickness of 8 mm will not be appropriate, so it is expected that die errors will occur. When the values are compared, it has been seen in the analyses that D2 tool steel has a longer life than A2 steel in terms of fatigue life.

Finally, the safety factor of the matrix elements was examined with the "Safety Factor," which is the Fatigue analysis option. Fatigue Safety Factor analyzes are shown in Figure 9.

Safety factor values are given in Table 6. Surfaces with a safety factor of less than 1 are shown in red. As a result of these analyses, it was concluded that the first contact edges of the 6 matrix elements analyzed were risky areas and could be damaged before their fatigue life. The highest safety factor is in a D2 steel 12 mm thick matrix.

4. Results and Discussion

Analyzes were made with the Static Structural solution in the Ansys Workbench 2019 R2 program for drilling the transfer dies with the progressive two-axis die transport system. Two methods are used to determine the shear force to be applied before the analysis study.

Table 5. Matrix fatigue analysis min. cycle values

Material	Matrix Thickness (mm)	min. Lifetime Value
D2	8	16194
	10	3,4715 e5
	12	1,1233 e7
A2	8	0 - 10000
	10	1,4549 e5
	12	5,6572 e6

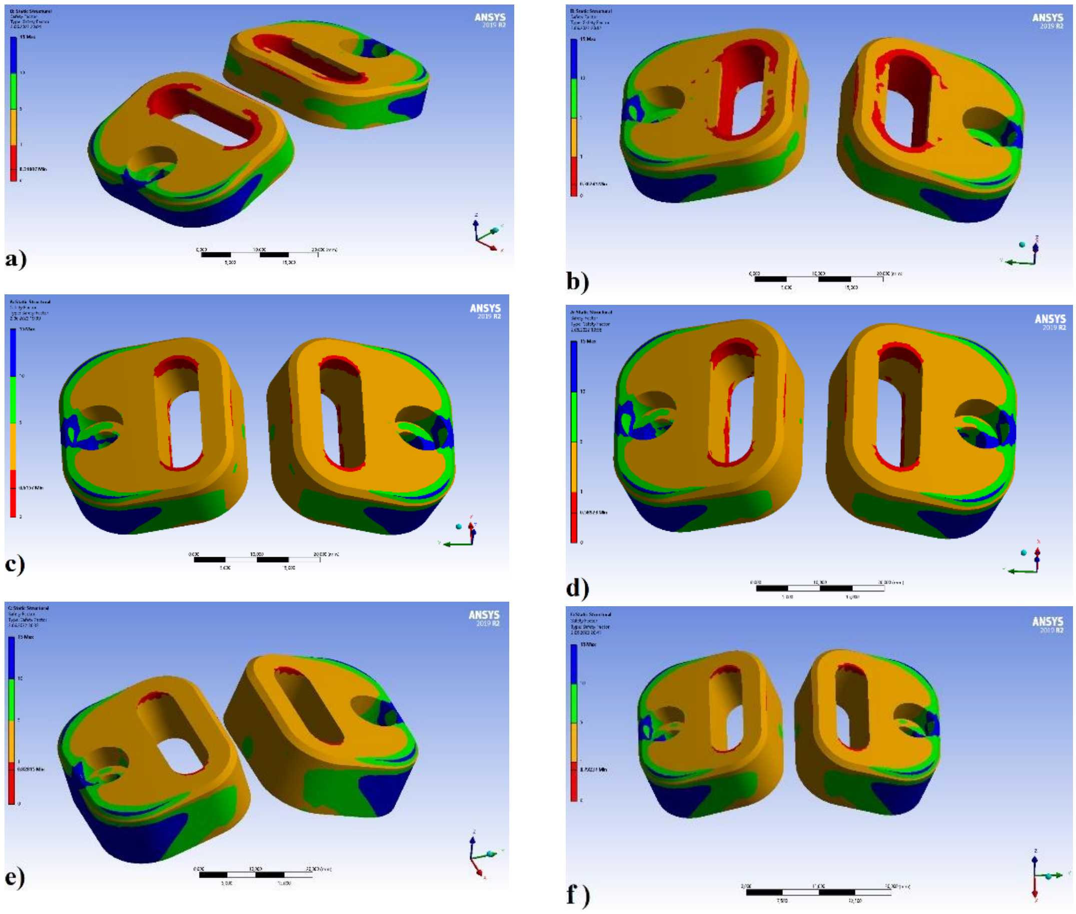

Fig. 9 Safety factor analysis of shearing force applied matrices, (a) 8 mm, D2 tool steel, (b) 8 mm A2 tool steel, (c) 10 mm D2 tool steel, (d) 10 mm A2 tool steel, (e) 12mm D2 tool steel, (f) 12 mm A2 tool steel

Table 6. Matrix fatigue analysis min. cycle values

Malzeme	Matrix Thickness (mm)	Min. Safety Factor
D2	8	0.31607
	10	0.6157
	12	0.82815
A2	8	0.30241
	10	0.58923
	12	0.79237

Method 1: Drilling operation die elements; sheet material, punches, matrices, and matrix retainer are run in Ansys Workbench 2019 R2 finite element software. Analyzes can be performed using the Explicit Dynamic methods for the drilling operation. For these analyses, after the DP600 material definition is made for the sheet metal part, AISI D2

and AISI A2 tool steels are defined as materials for the die elements, respectively. After the material identification process, necessary connections are made between the die elements. For punch hole analysis, this process is performed by giving one of the forces, speed, or distance range values. After the drilling operation, the force values of the punch from the surfaces in contact with the matrix are measured by the analysis program.

Method 2: The cutting force of the punches is calculated for the hole-drilling operation. The matrix surfaces in contact with the punch are determined by the result obtained, and static analyses are made for these values.

Method 2 was used in this study. The forces acting on the matrix during the drilling operation are considered the cutting force. İt is because it is foreseen that the punch will cut the sheet material and contact the matrix with the same intensity. Another reason for using this method is that these processes take a long time in the computer, where the finite elements will be made for the drilling operation. One of the goals of future studies is to compare the resulting difference using method 1.

When the analysis results were examined, it was seen that the Von-Mises stress values were the same for both materials. İt is because the mechanical properties of the two selected tool sheets of steel are close to each other. In total deformation values, A2 material undergoes an average of $2.4e^{-4}$ mm less deformation than D2 tool steel.

The fatigue analysis results, which is the study's main purpose, were compared. These results show that D2 material can operate at longer cycle times than A2. Increasing the matrix thickness had a positive effect on the lifetime analysis. In the fatigue safety factor analysis, the min. The safety factor was found to be more reliable than that of A2 tool steels. To verify these analyzes, the performance and working conditions of the progressive + biaxial transport die in mass production should be evaluated. Future studies aim to use powder metallurgy-based materials with higher yield and rupture strengths. It is aimed to evaluate the materials to be analyzed by running them under production conditions.

5. Conclusion

This study investigated the final process of sheet metal forming dies using a progressive two-axis in-die conveying system designed with Catia V5 software. Life analyzes of the matrix element used in the hole drilling process was made with Ansys software, which applied the finite element method. Obtained results are given below.

- The analyses made for the hole drilling process concluded that the highest stress value was on the matrix retainer when the whole die was evaluated. The highest stress value on the matrix is 650.52 MPa in the 8 mm thick matrix in A2 tool steel. Since this value is lower than the yield strength of A2 tool steel, its use is not critical. The lowest Von Mises Stress was obtained in the matrix of 10 mm thickness in both A2 and D2 tool steels.
- In the life analyses, it has been seen that the matrix element can show an infinite life when designed with D2 steel material and 12 mm thick.
- The cycle number of the matrix designed with A2 material and 8 mm thickness achieved the lowest cycle value compared to other designs in the other study. For this reason, it was concluded that this design is unsuitable for real production conditions.
- Fatigue analysis was also evaluated with the safety factor. It has been observed that the 12 mm thick matrix made of D2 tool steel has the highest safety factor.
- According to the test results, fatigue analysis improves as the matrix thickness increases. The matrix with the best life analysis and the safety factor comprises 12 mm thick D2 tool steel. During the design, It was concluded that when the matrix thickness is 12 mm, the dimensions of the matrix retainer should also be changed. However, the process designed for 12 mm matrix thickness was unsuitable for the die with a progressive + biaxial conveying system.
- The design space for the drilling process is narrow. As the matrix size increases, multiplication problems in the die are expected. The other best result is the 10 mm thick D2 tool steel matrix. Fatigue life is 347,150 cycles. This value was found to be sufficient for the die design that was required to perform at least 179.000 drilling operations. It was concluded that a 10 mm thick matrix is suitable for the dimensional design of the die. With the analysis results and experience, it was decided to use 10 mm thick D2 steel matrices to produce the suspension wedge piece.
- A comparative evaluation of the matrix fatigue behavior of the die to be used in mass production will be made with the analysis outputs obtained in future studies.

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