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An Investigation of the Effects of a Sheet Material Type and Thickness Selection on Formability in the Production of the Engine Oil Pan with the Deep Drawing Method

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Abstract

In internal combustion engines, in a way integrated under the engine block, the oil pan is used to store the engine oil, to separate foreign substances in the oil coming from the engine block, to lubricate the moving parts, to help the engine cooling system. In this study, by using different materials such as DC06 (IF), AISI 304, Al6082, and DC01 and selecting different thicknesses such as 1.5 mm and 2 mm, the deep drawing method was applied to them, and their formability behaviors with deep drawing were investigated. The effects of the sheet material type and thickness parameters on the tensile force and wall thickness variation on a sample engine oil pan formed by deep drawing were determined. Different parameters were determined for the sample engine oil pan. According to the analysis results, it was detected that the wall thicknesses of the sensitive points were determined to decrease by 0.86 mm, 0.62 mm, and 0.37 mm, respectively, for deep drawn samples with 1.5 mm thickness (AISI 304, DC06, DC01), but tearing occurred in the Al6082 material. On the other hand, when the sheet material thickness was increased to 2 mm, it was observed that the thickness change rates decreased by 13% in DC06, 0.7% in AISI 304, 33% in Al 6082, and 4% in the DC01 material type in comparison with the initial sheet thickness of 1.5 mm. The results of the analysis obtained in this study demonstrated that these four materials had superiorities over each other, that the thickness of the material was an essential criterion in deep drawing, and that the use of 2 mm thick AISI 304 material among the selected materials in the production of the engine oil pan was more suitable.

Keywords: Formability, Engine oil pan, deep drawing, Finite element analysis, Metal sheet, thickness distribution

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1. Introduction

A very significant part of the sheet metal products used in daily life are formed by the deep drawing method and offered for use. Deep drawing is the stretching process that gives the required geometric shape to the metal sheet by the mechanical movement of the drawing die set. The forming method, which consists of a lot of successive drawing processes, is called deep drawing [1]. As is observed in Fig. 1, in this method, with the help of a press machine with a suitable power, the punch, from the deep drawing die elements, applies a specified force to the material, and thus, a three-dimensional profile and depth of the metal sheet with a planar geometry are created. Containers that are required to have a high depth and must be obtained by drawing can also be created with a large number of processes. In order to obtain a complex shape with deep drawing, a sheet metal usually has to go through several steps, not one step [2]. In deep drawing processes, the complexity of all real events occurring in the production process leads researchers to theoretical analyses. The prototype manufacturing of parts such as dies and punches used during deep drawing processes is time-consuming and quite high cost. Before manufacturing dies and punches, working parameters such as ideal geometry and feasibility are determined in a numerical analysis program. Therefore, in deep drawing studies, theoretical and numerical analyses are carried out first. It is crucial to decide on the system's ideal geometry and feasibility before starting the manufacturing processes. Furthermore, operations can be calculated by finite element simulation, so it is possible to predict formability from the thickness and stress distribution and to verify the designed die for sheet metal [3].

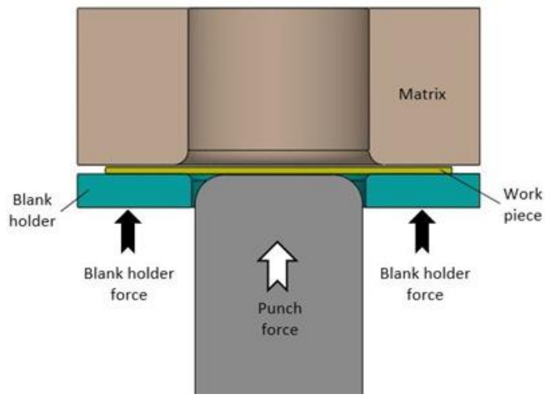


Fig. 1. Dies and elements used in deep drawing

The method of forming sheet metal materials with deep drawing is preferred to other manufacturing methods due to its product quality, production speed, and cost advantages. In the deep drawing method, which is widely and simply applied in the industry, while the metal sheet is drawn into the die, it wraps around the punch, meanwhile many complex parameters that affect the drawing process must be followed. For this reason, ideal parameter values should be selected and applied in order to perform the deep drawing process appropriately [4,5]. Pressure plate force, punch force, initial part geometry, chemical and physical structure of the material, heat treatment applied to the material, rolling direction, die matrix and punch radiuses, drawing speed, and forming temperatures are the parameters that affect the appropriate realization of the deep drawing method.

Kim et al. investigated an oil pan form in a single and multi-stage manner with the hydro mechanical deep drawing method and stated that the multi-stage deep drawing creates lower strains in the piece [6]. Yanarocak et al. carried out an optimization study for the diesel engine oil pan using layered steel material and subjected the material to different strength tests and achieved a 55% improvement in the design [7]. Subramanyam et al. performed die design optimization for the aluminum cast oil pan used for internal combustion engines [8]. Özdemir et al. performed the analyses of six different materials used in the automotive industry by using the finite element method and examined the formabilities of the materials. As a result of the analyses, it was determined that niobium, titanium, and vanadium elements affect formability negatively, while aluminum has positive effects [9]. Rajendraprasad et al. performed static and dynamic analyses on the engine oil pan using the finite element analysis program [10]. Chen et al. performed experimental analyses and simulations of the engine oil pan from a hybrid metal sheet with the progressive hydromechanical deep drawing method and determined its advantages [11]. Takuda et al. examined the formability of the AISI 304 material with the deep drawing method at different temperatures (150 °C, 300 °C, and 350 °C) and detected that the temperature effect reduced the possibility of earing and tearing [12].

The researchers established the sheet forming simulation procedure and determined its accuracy on different sheets [13-15]. Lee et al. performed an optimization of size and thickness using ultra-light steel material for a car front door [16]. Colgan and Monaghan investigated thickness change and molding force in deep drawing by experimental methods and finite element analysis [17]. Cheng et al. conducted a study with the aim of eliminating wrinklings that occurred as a result of deep drawing in materials to increase lightness and vibration removal performance in automotive applications [18]. In the literature, there are analytical [19, 20] and experimental [21-23] studies in which the change of product thickness as a result of deep drawing with the increase in the deep drawing ratio and height of metal sheets is investigated.

In order for the product to be obtained as a result of the deep drawing process to be of the desired quality, the analysis process should be well planned, and in order to prevent errors such as tearing and earing, attention should be paid to the selection of material, sheet thickness, and ambient and process parameters, which affect the deep drawing process [24]. In order to be able to select and apply the right parameters, it is necessary to determine the sensitive areas in the product by repeating deep drawing experiments with numerous die sets in the design and to determine the most appropriate initial sheet thickness and other technical information required for deep drawing. Finite element analysis is needed to avoid the cost and time problems that these operations will bring. In this study, the effects of sheet metal material and initial thickness differences, which are the most critical factors in deep drawing, on the stresses occurring in the drawn container-shaped piece and on the change of the product wall thickness were investigated. In this context, deep drawing analyses for two different thickness values of 1.5 mm and 2 mm, for each of the four different material types (DC06, AISI 304, Al 6082, and DC01) were performed using the Simufact.forming program. The deep drawing characteristic results of these materials with different properties were compared graphically with each other.

2. Material and Method

In the study, a sample engine oil pan was designed using the SolidWorks program in order to clearly see the deep drawing behaviors of four different material types that are suitable for deep drawing and most widely used in automotive and other sectors. The designed engine oil pan is presented in Fig. 2. In order to produce the designed sample oil pan with the deep drawing method, necessary calculations and die set designs were carried out.

Fig. 2. Sample engine oil pan design

Apart from formability, each type of material selected has its own distinct advantages and disadvantages. Without paying attention to them, only the formability characteristics with the deep drawing method were examined. A two-stage process was applied in order to prevent tearing in the deep drawing die design for the production of a sample engine oil pan. The image of this two-step process is given in Fig. 3. Deep drawing products with a high limit draw ratio in the elliptic or rectangular form are subjected to a multi-stage deep drawing process [25,26]. Thus, it is ensured that the final product has the desired quality, but the die design both prolongs the production process and increases costs. However, these losses can be compensated by conducting an optimization study before production with a suitable simulation program.

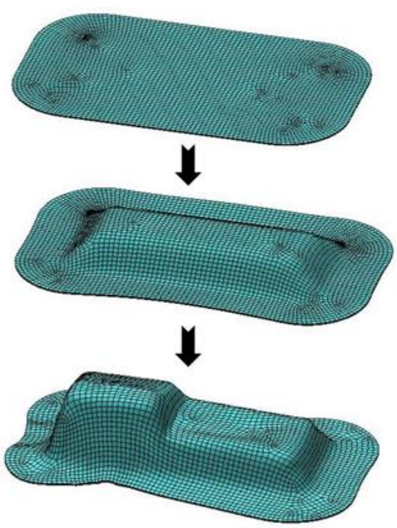
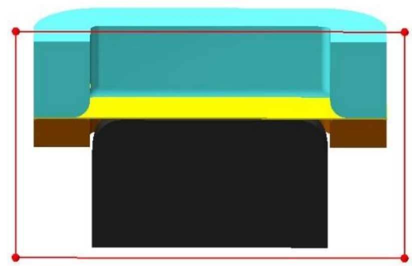
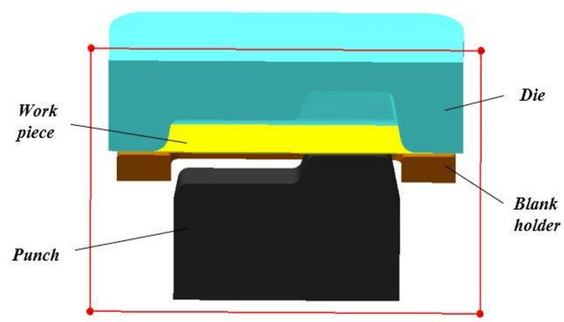


Fig. 3. Deep drawing stages

In the study, two different special die and punch sets were created for two-stage deep drawing processes. In the first stage, with the die set in Fig. 4-a, the deep drawing process up to a 30 mm depth is applied, then by using the die set shown in Fig. 4-b, the deep drawing process up to a 70 mm depth, which is the final stage, is performed. The drawing rate and friction coefficients were kept constant in the hydraulic press used in deep drawing processes.



(a)



(b)

Fig. 4. Deep drawing stages cross-sectional view of the die

In this study four different types of materials (DC06, AISI 304, Al 6082, and DC01) of which technical features were given in Table 1 and which were suitable for deep drawing and widely used in the production of automotive parts were selected. Two different thickness values, 1.5 mm and 2 mm were preferred for theoretical analysis studies. The mechanical and chemical properties of the selected metal sheet materials are presented in Table 2 and Table 3.

Table 1. Names and usage areas of the materials used

Material Type	Metal sheet usage characteristics
DC06 (DIN EN 1030) (IF Steel)	Aging resistant, with very low carbon c ontent, extra deep drawing sheet
AISI304 (DIN 1.4301) (X5CrNi189)	Stainless steel most widely used in the automotive industry, home applian ces, and industrial kitchens
Al 6082-T6 (DIN 3.2315)	Aluminum with medium strength, which is artificially aged by solution treatin g and is used in aviation, aerospace ind ustry, and machinery manufacturing
DC01 (DIN EN 1030) (St12)	Steel sheet with general use suitable for the deep drawing process

Table 2. Chemical properties of materials

Material Type	DC06 (IF)	AISI 304	Al 6082	DC01
C [%]	0.02	0.08	-	0.12
Mn [%]	0.25	2.0	0.40	0.60
P [%]	0.02	0.045	-	0.045
S [%]	0.02	0.03	-	0.045
Al [%]	-	-	95.2	-
Cr [%]	-	18	0.15	-
Ti [%]	0.3	-	-	-
Zn [%]	-	-	0.2	-

Table 3. Mechanical properties of materials

Material Type	DC06 (IF)	AISI 304	Al 6082	DC01
Yield Strength (MPa)	170	210	260	280
UTS (MPa)	330	505	310	410
Elongation (%)	41	70	19	28

The deep drawing process applied to the designed sample engine oil pan was performed in the finite element analysis Simufact program. Since the low deep drawing rate will facilitate the material's change of shape the hydraulic press was chosen and its drawing rate was set at 3 mm/s. First of all in order to determine the appropriate pressure plate force in deep drawing without the occurrence of problems such as tearing and wrinkling necessary calculations were made and applied for each material type according to Eqs. (1-3) [5].

$$F_{bh} = 0.015\sigma_y \pi [D^2 - (d + 2.2t + 2r_d)^2]/4 \quad (1)$$

$$F_{bh} = \frac{F_{dd}}{3} \quad (2)$$

$$F_{bh} = [(\beta - 1)^2 + \frac{D}{200t}]\frac{\sigma_{uts}}{400} A_{bh} \quad (3)$$

In order to enable the easy flow of sample sheets into the die with the effect of punch force on the die elements during deep drawing the Coulomb friction model which is the most suitable for dry friction was selected [27]. According to the selected parameters, a two-stage deep drawing process was applied and the obtained results (effective plastic strain, thickness, deep drawing force and punch force) were evaluated.

3. Results and Discussion

When a single-step deep drawing process is applied to form the product, high strains occur in the sensitive (sharp corners, etc.) areas, and these strains can create undesired thinnings or tearings in the thickness of the wall. Therefore, a two-stage deep drawing process was carried out. For the 1.5 mm thickness of four different materials, the percentage strain values that occurred in the first stage deep drawing are presented in Fig. 5. Strain and thickness graph values were taken as a percentage in order to make the comparisons better.

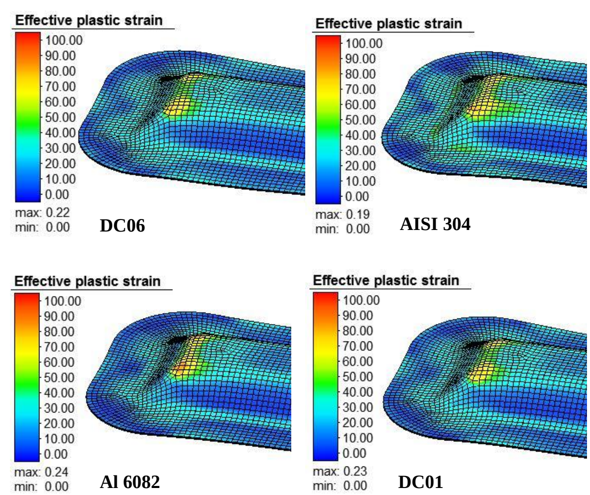


Fig. 5. First stage molding, 1.5 mm strain views

The strain views that occurred in the second stage deep drawing process for 1.5 mm thicknesses are presented in Fig. 6. Strain and thickness graph values were taken as percentage in order to make the comparisons better. The maximum strain occurred in the material type of Al6082 (0.85), which resulted in tearing. Strain values were found to decrease as DC06 (0.64), DC01 (0.59), and AISI 304 (0.43), respectively.

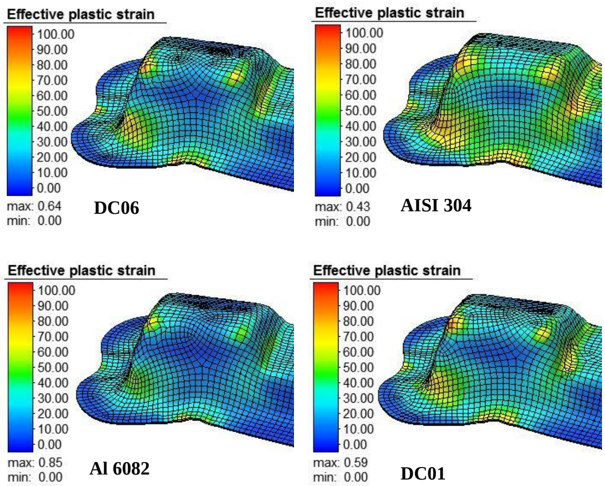


Fig. 6. Effective plastic strain values in a 1.5 mm initial thickness, in the second stage applied to the pan (%)

In the second stage of deep drawing processes, the % wall thickness distribution values in the critical areas for a 1.5 mm initial thickness are shown in Fig. 7. During the process, thinning and then tearing were observed to occur in sensitive areas of the model, which was created from the Al 6082 material. It was determined that thinning occurred in other materials, but no tearing occurred. While the best performance of the minimum thickness values in sensitive areas was obtained to be 0.86 mm in the AISI 304 material, it was found to be 0.62 mm and 0.37 mm in the DC01 and DC06 materials, respectively. At maximum thinning points, thickness change rates for 1.5 mm initial sheet thicknesses were 75% for DC06, 42% for AISI 304, 99% for Al 6082 (tearing), and 58% for DC01.

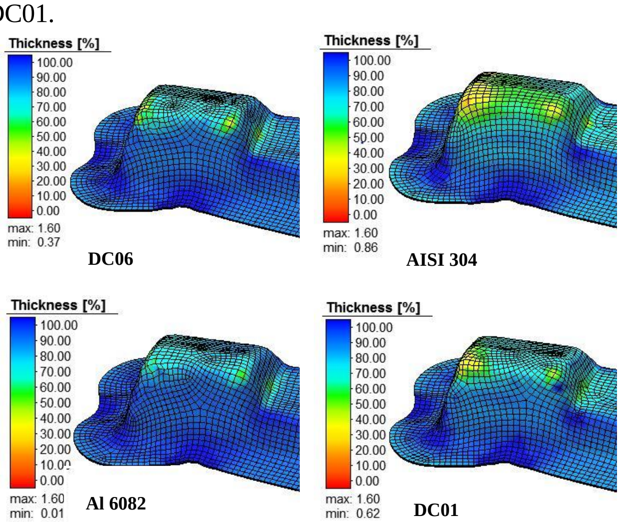


Fig. 7. Thickness distributions in a 1.5 mm initial thickness, in the second stage applied to the pan (%)

In the second stage applied to the pan, the thickness distributions for a 2 mm initial thickness were shown in Fig. 8. The sequencing of the maximum thinning that occurred in the materials was similar to the results of the experiment performed with a 1.5 mm initial sheet thickness; only the thinning rates decreased. As is observed in Fig. 8 no tearing occurred in any material. While 1.16 mm occurred in the AISI 304 material, it was followed by DC01 (0.91 mm), DC06 (0.76 mm), and Al 6082 (0.68 mm) materials, respectively. At maximum thinning points, thickness change rates for 2 mm initial sheet thicknesses were 62% for DC06, 42% for AISI 304, 66% for Al 6082, and 55% for DC01.

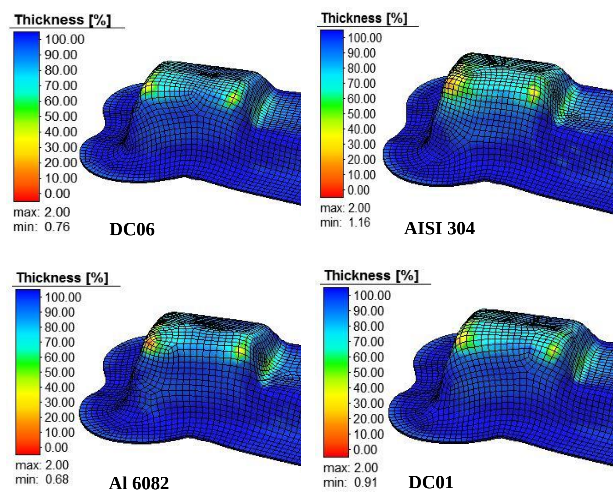


Fig. 8. Thickness distributions in a 2 mm initial thickness, in the second stage applied to the pan (%)

With the help of the values obtained from the analysis results given in Fig. 7 and Fig. 8, the pan's maximum thinning points with the risk of tearing can be observed. In the engine oil pan model, the homogeneous distribution of these thickness changes everywhere is also quite important, as well as the thinning at the sensitive points. Furthermore, in order to see the general thickness distribution more clearly, the thickness distribution was examined by taking a longitudinal section from 65% of the crankcase width, as is observed in Fig. 9. In order to see this distribution, 30 different points were determined by selecting important points such as the beginning end and middle of the radiuses along the pan section and the thicknesses at these points were detected.

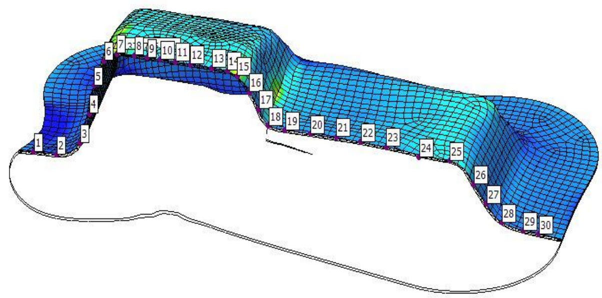


Fig. 9. Cross-section (65%) view of the points of which thickness distribution is examined in the final product

The graphs for four different materials and initial thicknesses (1.5 and 2 mm) in the result of the investigation are observed in Fig. 10 and Fig. 11. In order to be able to compare the thickness change at 30 points throughout the product, the thicknesses were demonstrated as a percentage in all four different material types according to both different initial thicknesses. The maximum thickness change in both initial sheet thicknesses occurred between 6 and 8 points. It is observed that the order of thickness change rate increase at the end of forming occurs as AISI 304, DC06, DC01, and Al 6082, and this does not generally change throughout the whole part, not only at the points where maximum thinning occurs.

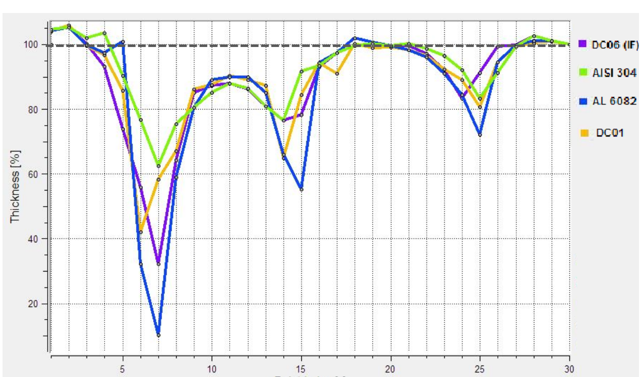


Fig. 10. Point (%) thickness values of the product for a 1.5 mm initial sheet thickness

When the maximum thinning points are evaluated according to the initial sheet thicknesses, in comparison with 1.5 mm, the thinning rate in products shaped with a 2 mm thickness was 13% less for DC06, 0.7% less for AISI 304, 33% less for Al 6082, and 4% less for DC01. According to the results obtained, it was determined that the initial sheet thickness was not very effective in the deep drawing process in AISI 304 stainless steel sheets, but it was extremely significant for the Al 6082 sheet material.

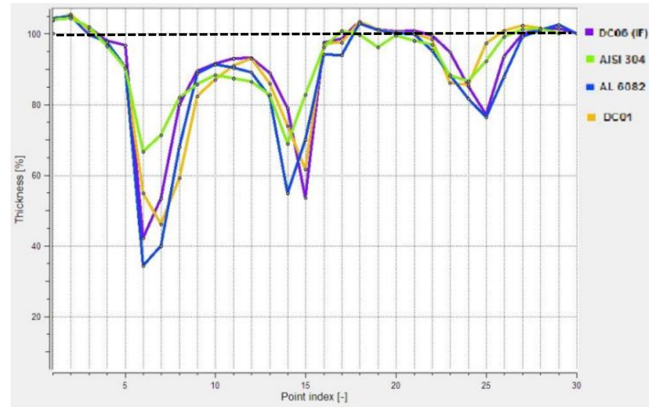


Fig. 11. Point (%) thickness values of the product for a 2 mm initial sheet thickness

Punch and total deep drawing forces are also important in evaluating deep drawing processes. Punch forces that occurred in four different types of materials are presented in Fig. 12-a and Fig. 12-b graphs. A minimum punch force of 70 kN occurred in the 1.5 mm thick material type Al 6082, while 100 kN force occurred in the material with a 2 mm thickness. However, the punch forces in the other three types of material samples increased considerably. The highest punch force occurred in the AISI 304 material, while DC06 and DC01 material forces were similar to each other. At a 2 mm thickness, these forces increased at a certain rate without changing their order. The total deep drawing forces are observed in Fig. 12-c and Fig. 12-d graphs. These forces are the sum of the pressure plate forces and punch forces. The deep drawing forces occurred in proportion to the punch forces.

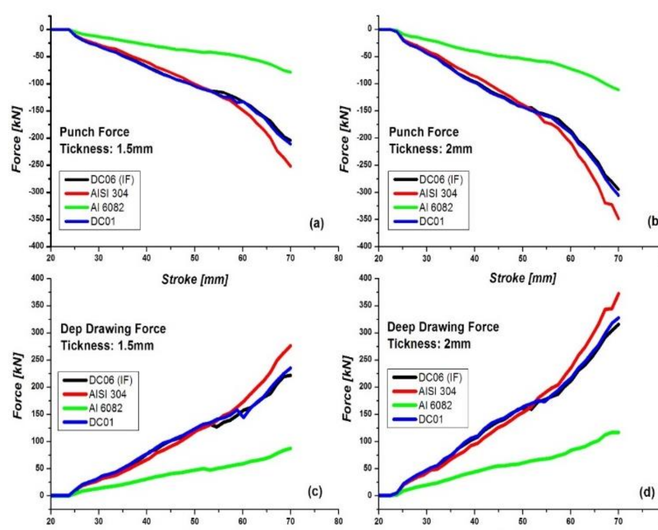


Fig. 12. Punch forces (a) and total deep drawing forces (b) that occurred in deep drawing processes

Effective plastic strains that occurred in the materials as a result of deep drawing are given in Fig. 13. In Fig. 13-a, the highest strain occurred for a 1.5 mm thickness in the AISI

304 material as 0.20, while effective plastic strains for other types of materials remained around 0.10. In Fig. 13-b, as a result of the deep drawing process in a 2 mm initial sheet thickness, effective plastic strains for all materials in the piece occurred around 0.15.

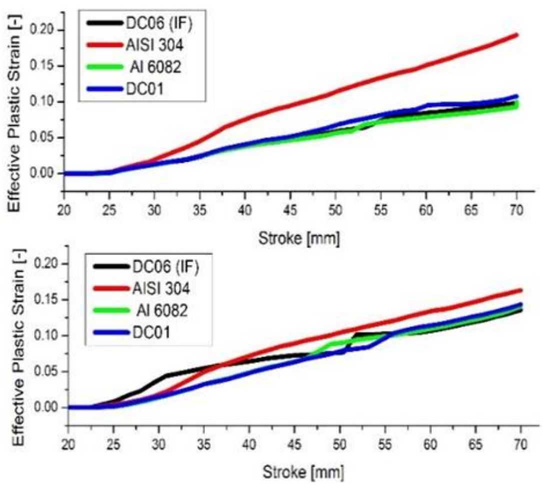


Fig. 13. Effective plastic strains that occurred in the initial thicknesses of 1.5 mm (a) and 2 mm (b)

4. Conclusions

In this study on a sample oil pan used in internal combustion engines, four different metal sheet types (DC06, AISI 304, Al 6082, and DC01) which are suitable for deep drawing and widely used in the industry, with two different initial thicknesses (1.5 and 2 mm), were subjected to the deep drawing process in a finite element analysis program. As a result, the final product sheet thickness distributions, formed strains, and molding force graphs were obtained. Although each type of material selected has its own distinct advantages and disadvantages apart from formability, only the formability characteristics with the deep drawing method were examined without paying attention to them.

The most suitable material type for a product in the form of a sample oil pan was determined to be the AISI 304 material, but the highest punch and total deep drawing forces were observed to occur in this material. As a result of deep drawing processes, the strains formed in 1.5 mm initial sheet thicknesses were 0.2 in 70 mm stroke in the AISI 304 material type, while in other types of materials, values around 0.1 close to each other were obtained. In the 2 mm initial sheet thickness, this value decreased to approximately 0.15 for all material types. The lowest force stresses in the total deep drawing and punching forces occurred on Al 6082, and for other material types, these forces were close to each other and, on average, three times higher. In deep drawing processes, it was observed that severe thinning occurred in sensitive areas in all four material types and even tearing occurred in the Al6082 material type for a 1.5 mm thickness.

When the maximum thinning points were evaluated by taking the initial sheet thicknesses as a reference, in comparison with the thickness of 1.5 mm, in a 2 mm thickness, the maximum thinning rates decreased by 13% in DC06 (IF), 0.7% in AISI 304, 33% in Al 6082, and 4% in the DC01 material type. According to these values, the increase in the initial sheet thickness is observed not to be effective in the AISI 304 stainless steel material type in deep drawing processes. However, the initial sheet thickness was determined to be extremely important for the Al 6082 material. Moreover, according to the results obtained in the study, it was observed that in forming with deep drawing for the pan sample, the best initial sheet thickness was 2 mm, and the material type was AISI 304.

Nomenclature

D	: Blank sheet diameter
F_{avg}	: Average molding force
F_{bh}	: Blank holder force
F_{dd}	: Deep drawing force
h_{max}	: Maximum punch stroke
P_{bh}	: Blank holder pressure
t	: Sheet thickness
β	: Deep drawing ratio
σ_{uts}	: Ultimate tensile strength
σ_y	: Yield strength

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