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Original Research

Numerical Simulation of Mechanical Joining of Three DP600 and DC06 Steel Sheets

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Abstract

There are many reasons to utilize various grades of steel in car body production. Automotive producers tend to choose steels with great formability and the capacity to absorb impact energy. The dominant method used for joining car body sheets has for many years been resistance spot welding, but the use of various steel sheets leads to research into alternative joining methods. Mechanical joining - clinching, is the innovative method to join these materials. Numerical simulation tools are used to optimize the joining of materials. Simufact Forming software was used to analyse the clinching joining of three sheets of material DP600 and DC06. According to the axisymmetric character of the mechanical joining process, the simulation was stream-lined to a 2D representation. The results of the simulation of the mechanical joining process were compared with the real samples prepared for metallographic observation.

Keywords: DC06, DP600, clinching, FEM analysis

1. Introduction

The main issue in the automotive industry are the solutions for improving the lightweight of the cars and improved crash reaction of explicit car-body structures. Achieving these aims leads to the use of different grades of steel sheets in different parts of the car body (Kaščák et al., 2016). Materials from extra deep-drawing grades to ultra-high strength grades are therefore utilized. The dual-phase steel sheets are distinguished by the combination of high strength and good formability because of their specific microstructure (the hard martensitic or bainitic phase is dispersed in a ferritic matrix). This specific type of material is characterized by an acceptable ability to redistribute stress and improve mechanical properties (Bzowski et al., 2018; Qin et al., 2020; Spena et al., 2019). Extra deep-drawing grades are characterized as cold rolled steel and are mostly designed for cold forming, suitable for multifaceted large scale pressworks of automobile bodies (Behrouzi et al., 2014; Livatyali et al., 2010; Neto et al., 2017). Resistance spot welding is used as the primary method of joining of steel sheets, but the use of various grades of materials leads to research into other joining methods.

Clinching, as one of a mechanical joining methods, is an innovative technique to join various grades and thicknesses of materials. In general, the principle of the process of clinching consists of interlocking the sheets together using a specially shaped punch and die. At the stage of contact of the material and the specially shaped die, the material flows to the sides and creates a clinched joint. The resulting interlocking between the joined materials is an important factor for the creation of a high-quality clinched joint with sufficient load-bearing capacity (Kaščák et al., 2017; Lambiase, 2013; Shi et al., 2020). To optimize the joining of materials, the means of numerical simulation are advantageously used. They make it possible to predict the behaviour of materials during the joining process (Pater et al., 2021; Potgorschek et al., 2020).

Most of the research is aimed at evaluating the properties of joints formed on two sheets. Only a few studies concern the evaluation of joints formed on three sheets. The paper deals with the simulation of the process of clinching DP600 and DC06 steel sheets, and by comparing the results of the simulation with the clinched joints that were created.

2. Methodology of the research

2.1. Used materials

In the experimental part of this article, two types of materials were used – DP600 (dual-phase high-strength grade) and DC06 (extra deep-drawing grade) steel sheets. The thickness of both steel sheets was 0.8 mm. Table 1 shows the basic mechanical properties of the DC06 and DP600 steel sheets, which were used on basis of the material list. The samples were prepared to a size of 40 x 90 mm (overlap length of 30 mm). Since it is a mechanical joining, it was not necessary to clean the surfaces of the samples.

Table 1. Basic mechanical properties of the observed materials

Material	E, GPa	A_{80}, %	$R_{p0.2}$, MPa	R_m, MPa	Strain hardening exponent n90 min.
DC06	210	41	142	330	0.220
DP600	206	23	407	633	0.216

2.2. Principle of clinching

Mechanical joining - clinching is an innovative technique to join progressive materials. The principle of the process of clinching consists of interlocking the sheets together using a specially shaped punch and die. At the stage of contact of the material and the specially shaped die, the material flows to the sides and creates a clinched joint. The interlocking creation is important for the creation of mechanically clinched joints to carry the load. The process of clinching is demonstrated in Fig. 1. A specially shaped punch with the diameter of ø5 mm and a die with the diameter of ø8 mm were used. Specially shaped punch and die were made of material grade 1.3343. Grade 1.3343 is the HSS-type steel. HSS refers to high-speed steel grade. The grade is defined in ISO 4957. The parameters of the clinching process are described in Table 2.

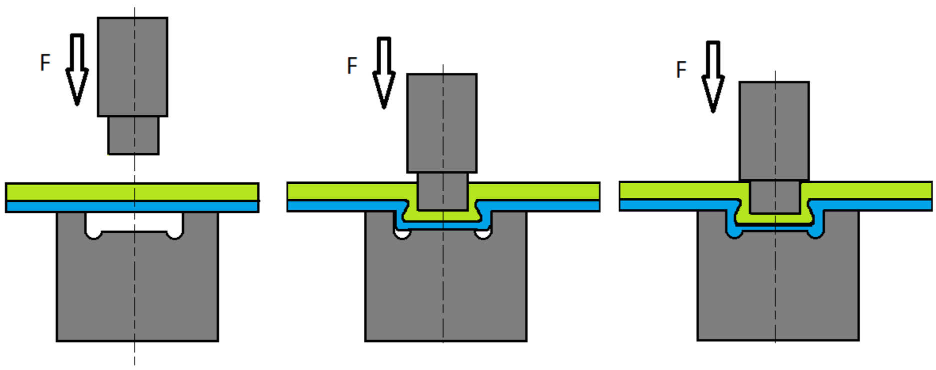

Fig. 1. Process of the mechanical joining – clinching

Table 2. Parameters of the clinching process

Material	Joined sheets	Pressing force F, kN	Punch diameter, mm	Die diameter, mm
DP600 (0.8 mm)	3	70	ø5	ø8
DC06 (0.8 mm)	3	70	ø5	ø8

2.3. Metallographic observation

During the stage of metallographic observation, changes in the microstructure of DP600 and DC06 steel sheets after the process of mechanical joining - clinching were observed. Interlocking, the value of the thickness of the bottom of the joint, the value of the thickness of the neck of the joint as well as the defects of the joints formed by the process of mechanical joining - clinching were observed as well. Microscopic observation was realized by KEYENCE VHX- 5000 light optical microscope (Fig. 2).

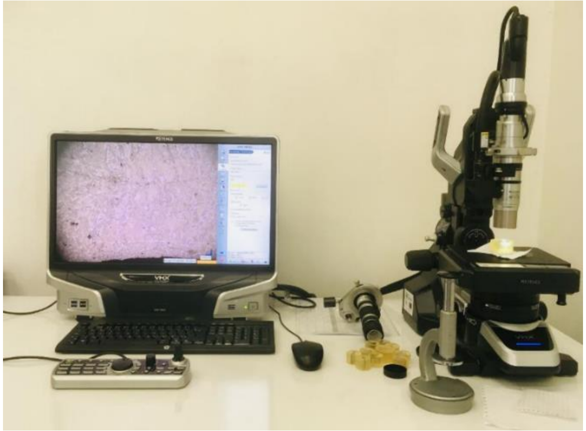

Fig. 2. KEYENCE VHX- 5000

2.4. Simufact Forming software

Simufact Forming software is a simulation tool for optimizing forming technology. This software includes a module of mechanical joining, specifically designed for simulation of mechanical joining processes. Simufact Forming enables the use of both two-dimensional (axisymmetric and planar) and three-dimensional simulations in the same specific graphical user interface. Different types of materials specific to the process of forming technology can be simulated. Joining different thicknesses of the materials can be simulated as well. In practice, simulation software is used to optimize the joining processes before the values of parameters are implemented in the process (optimal values are selected) (Lambiase, 2013; Shi et al. 2020). The software environment of Simufact is shown in Fig. 3.

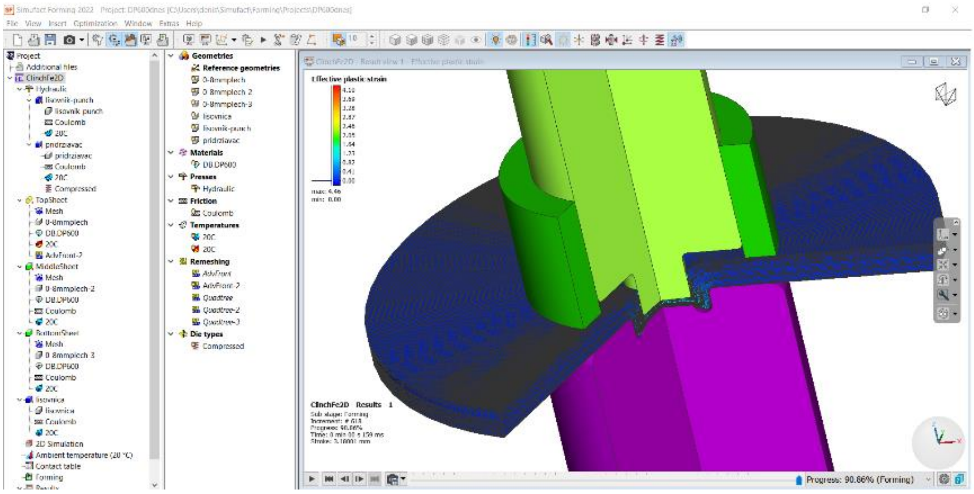

Fig. 3. The software environment of Simufact

The Simufact Forming was used for the mathematical representation of the solved problem and optimization of the joining process of mechanical joining – clinching of DP600 and DC06 steel sheets. As a part of the optimization of the mechanical joining process - clinching, different values of the punch stroke were evaluated with the simulation. Figure 4 shows the development of plastic deformation during the process of mechanical joining – clinching three DC06 steel sheets in the four characteristic joining steps.

The overall solution to the problem was simplified on a 2D model because the specially shaped tools and the created joint itself are axially symmetrical. The basic parameters necessary when defining the simulation itself include the friction coefficient, the holding force, and the specific distance of the punch stroke. During the simulation of the process of mechanical joining, the specially shaped punch can only be moved in the vertical position, with the punch making a vertical downward movement at a punch stroke. In the process of simulation, the punch can only be moved in the vertical position, with the punch making a vertical downward movement at the punch stroke of 1.8 mm, 2.2 mm, 2.5 mm, and 3 mm.

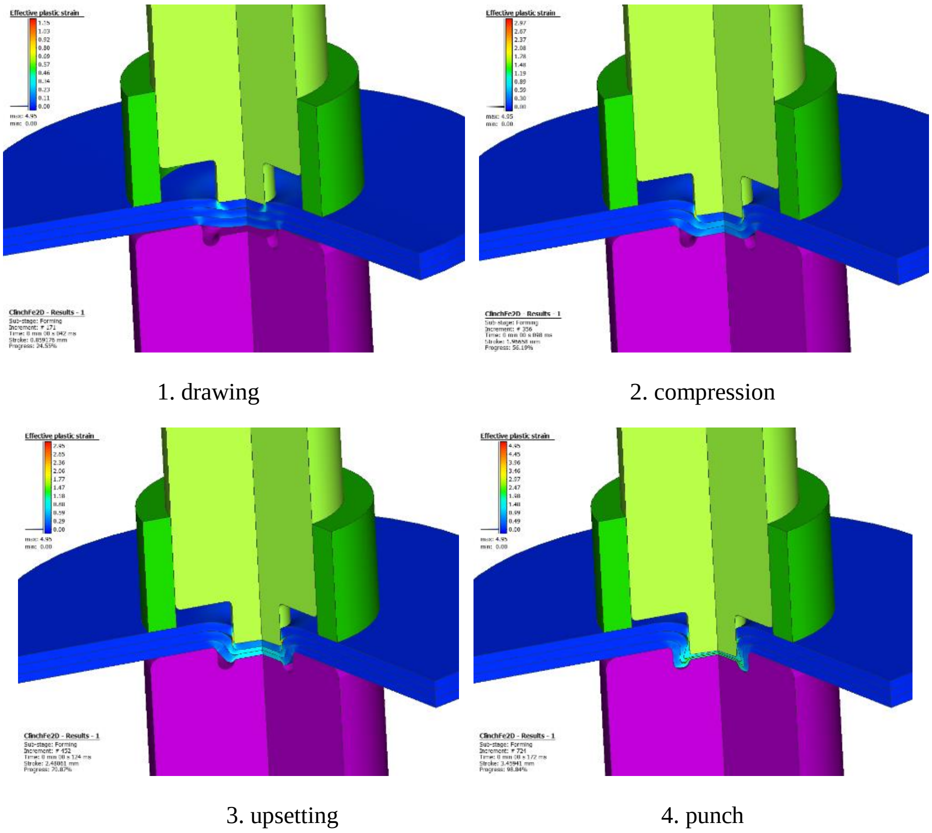

Fig. 4. Development of plastic deformation during the joining process

The contacts between the specially shaped tools and joined steel sheets (DP600 and also for DC06) as well as the contacts between the joined materials were defined as frictional contacts. Between specially shaped punch/die and sheets was defined as a friction coefficient of 0.12 and between three sheets was defined special friction coefficient of 0.2. The important and last boundary condition is the sheet holder force of 100 N that acts on the upper sheet to fix the joined materials during the process of the simulation. At the exact moment, the prescribed distance of the stroke height is reached, the special-shaped punch performs a backward movement to the starting position. At the same time, the special force of the sheet holder stops to work. The specially shaped punch, specially shaped die, and sheet holder were specified as perfectly stiff and non-deformable bodies. The joined sheets - a combination of three steel sheets for material DP600 and a combination of three steel sheets for material DC06 were defined as deformable bodies.

3. Results and discussion

When numerical simulation of three DP600 steel sheets was performed, a crack occurred at the value of punch stroke of 2.5 mm, in the area of interlocking (Fig. 5). On the other hand, numerical simulation of clinching of the three DC06 steel sheets was successfully completed at the value of punch stroke of 3 mm (Fig. 6). The critical area during the clinching process is the sheet metal on the punch side in the interlocking area. The maximum value of plastic deformation during the mechanical joining process of clinching is located just in the upper sheet at a certain point where it is excessively thinned. This area is known as the neck area of the clinched joint and is considered critical in terms of the process of mechanical joining. It is possible to verify the simulation to compare it and then verify the results with a real joining process. The experiments with real samples confirmed the results of the numerical simulation. When joining three steel sheets of DP600, the clinch joint did not form at all. There was a failure of the top sheet (from the punch side) in the interlocking area. The clinching of three steel sheets was successfully performed. The well-formed quality clinched joints were created. No defects were observed in the joints. The effect of the high stroke of the punch has a significant impact on the maximum effective plastic strain. The Simufact simulation software predicted the effective plastic strain for joints of DP600 sheets to the maximum value of 5.2%. For joints of DC06 sheets, the value of effective plastic strain was predicted to be max. 4.75%.

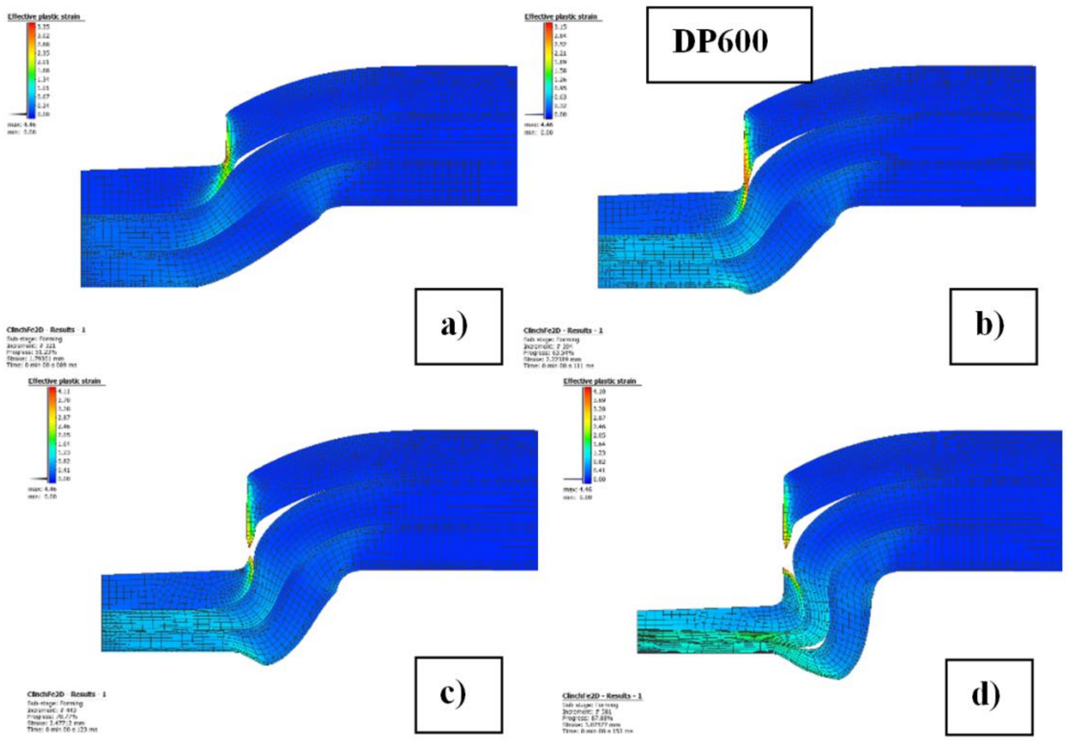

Fig. 5. Clinching of DP600 steels – punch stroke distance: a) 1.8 mm b) 2.2 mm c) 2.5 mm and d) 3 mm

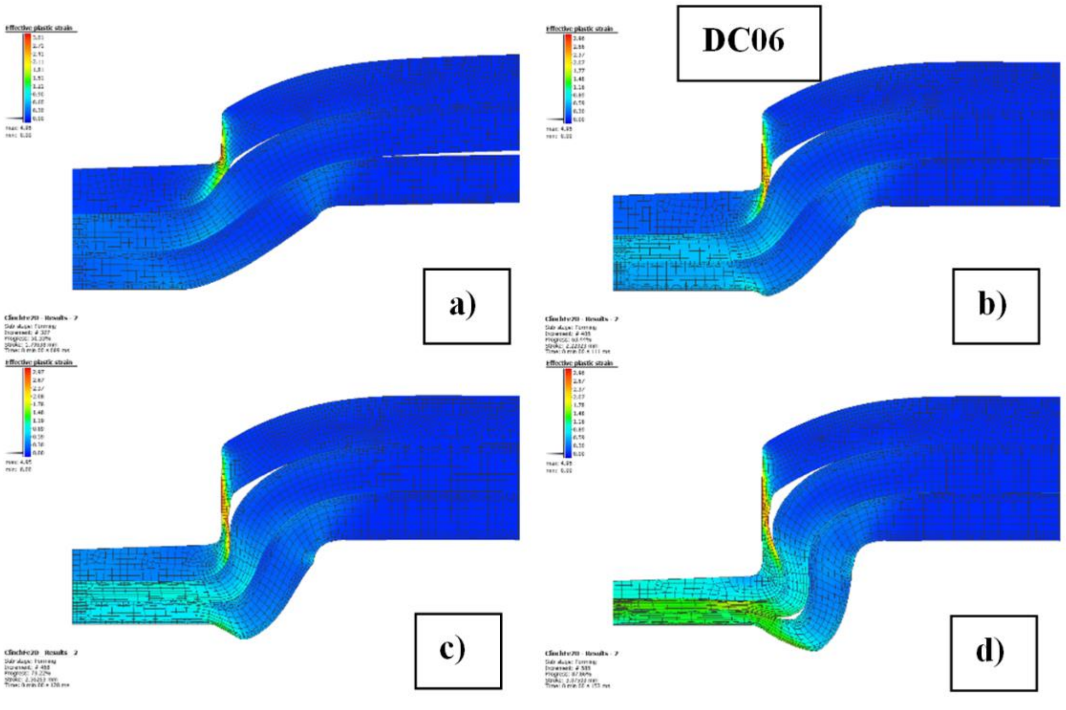

Fig. 6. Clinching of DC06 steels - punch stroke distance: a) 1.8 mm b) 2.2 mm c) 2.5 mm and d) 3 mm

Figure 7 shows a comparison of the cross-sections between the real joint created by the mechanical joining process - clinching (left side) and the joint resulting from the numerical simulation process (right side). The dimensions in the neck area of the joint were different; the simulation showed a large gap between the top and middle sheet (Fig. 7 – location A). Figure 8 shows the comparison of clinching joint parameters of real and simulated joints. The values in the area of the joint were within a certain tolerance identical for both the simulated joint and the real joint. Metallographic cut of the joint made of DP600 material was not realized, because the joint did not occur (which was also predicted by the simulation).

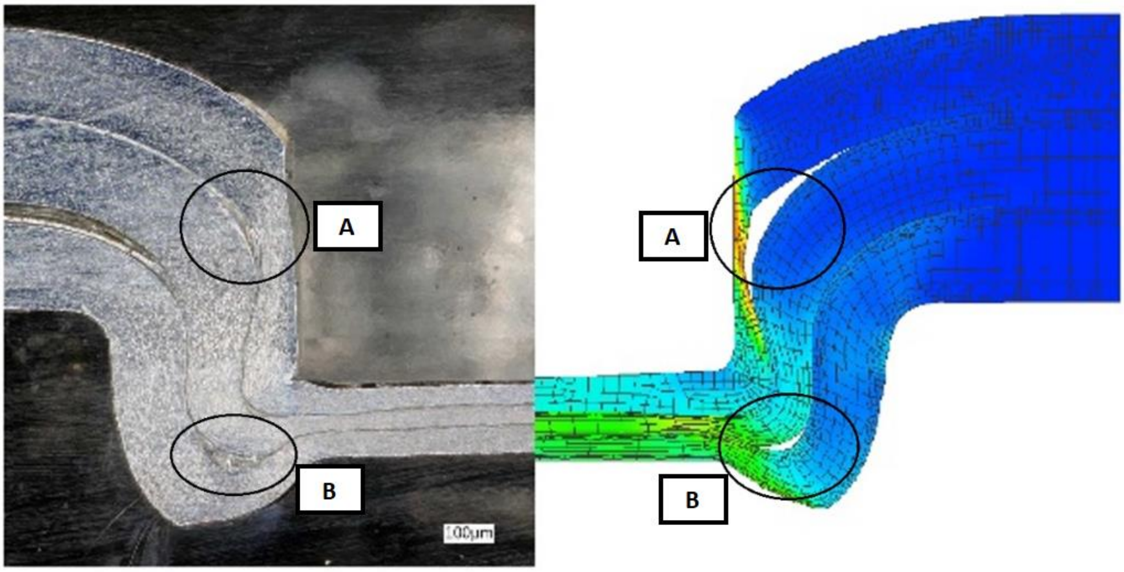

Fig. 7. Comparison of the cross-sections between the real joint created by the mechanical joining process of material DC06 - clinching (left side) and the joint resulting from the simulation (right side)

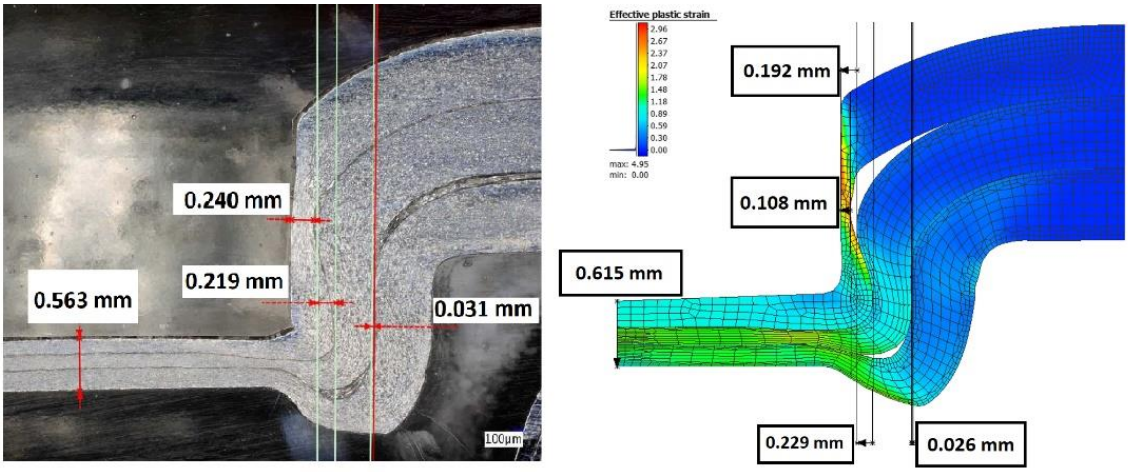

Fig. 8. Comparison of clinching joint parameters: a) real joint, b) simulated joint

4. Conclusions

The paper dealt with the numerical simulation of the clinching process of three steel sheets of various grades. The calculation of the simulation was simplified into 2D conditions based on the axial symmetry of the entire process of mechanical joining. The resulting simulation of the joining process in the form of the representation of the plastic deformation in the joining of three steel sheets (DP600 and DC06) during the individual mechanical joining stages was verified with the results of the real experiments.

The results from the experiments confirmed the results from the numerical simulation. When joining three steel sheets of DP600 quality, clinch joints were not successfully created. However, the joining of three DC06 grade steel sheets was successfully realized as was predicted by the numerical simulation.

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Symulacja Numeryczna Mechanicznego Łączenia Trzech Blach Stalowych DP600 oraz DC06

Streszczenie

Istnieje wiele powodów dla których warto wykorzystywać różne gatunki stali do produkcji karoserii. Producenci motoryzacyjni wykorzystują blachy stalowe o dużej plastyczności i zdolności pochłaniania energii uderzenia. Od wielu lat dominującą metodą łączenia blach karoserii samochodowej jest punktowe zgrzewanie oporowe. Zastosowanie różnych blach stalowych prowadzi do badań nad alternatywnymi metodami łączenia. Łączenie mechaniczne – przetłaczanie, to innowacyjna metoda łączenia tych materiałów. Numeryczne narzędzia symulacyjne służą do optymalizacji łączenia materiałów. Oprogramowanie Simufact Forming zostało wykorzystane do analizy łączenia przez przetłaczanie trzech arkuszy materiałów DP600 i DC06. Zgodnie z osiowosymetrycznym charakterem procesu łączenia mechanicznego, symulacja została uproszczona do reprezentacji 2D. Wyniki symulacji procesu łączenia mechanicznego porównano z rzeczywistymi próbkami przygotowanymi do obserwacji metalograficznych.

Słowa kluczowe: DC06, DP600, przetłaczanie, analiza MES