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SELECTION OF THE MINIMUM RADIUS OF THE PUNCH IN THE "CLINCHING" JOINING PROCESS FOR ACHIEVING MINIMUM JOINT STRENGTH FORCE

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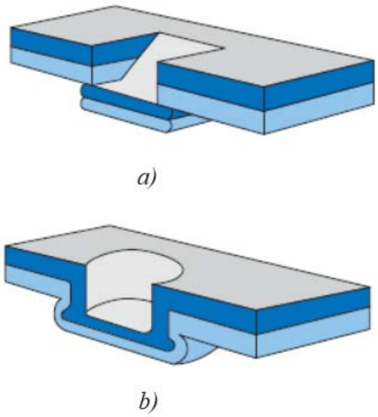
ABSTRACT

In order to meet the increasingly stringent requirements and growing needs of customers across most industrial sectors, particularly in the modern automotive industry, environmental protection, and energy consumption reduction, new materials and methods for their joining that cannot be performed using conventional joining technologies are increasingly being applied. The development of new metal joining technologies is moving towards reducing the use of additional materials and energy. In this regard, modern metal joining processes based on deformation processing principles are being intensively developed. One such material joining process, which presents a serious alternative to spot welding, is the "clinching" method. Clinching is a pressure-based joining technique aimed at joining thin sheets using specially shaped fasteners by plastic deformation of the base materials being joined. The quality of the formed joint is influenced by a number of factors. This paper presents the specifics of the clinching joining process and analyzes the impact of key process factors on the joint quality, with a particular focus on the effective determination of the punch radius required to achieve the minimal force necessary for the joint strength.

1. INTRODUCTION

It is well known that sheet metal joining is most commonly performed using the spot welding process. However, based on the increasingly apparent demands for flexibility, repeatability, cleanliness, production time, cost, energy consumption, environmental acceptability, temperature, residual stresses due to mechanical and thermal loading, and the characteristics of fatigue at the joint locations, the "clinching" joining technique has been intensively developed and used in recent decades. Its development goes hand in hand with the development of lightweight structures, or with finding solutions to problems that arise when joining parts of such structures and the requirements to increase their strength. Clinching can simply be defined as a method of fast, mechanical joining of two or more sheets by local plastic deformation without the addition of material or heat input. It is a cost-effective joining process in which parts, i.e., sheets, are joined in a single continuous manufacturing process consisting of partial penetration and subsequent pressure, thus forming a strong bond through plastic deformation. The mechanical properties of the formed joint are directly related to the mechanical properties of the materials being joined. There are two characteristic methods of clinching material joining in practice, depending on how the joint is formed, as shown in Figure 1. In the first case, the joint is created using shearing technology, i.e., partial cutting of the sheets being joined, as shown in Figure 1.a, while in the second case, the joint is formed by pressing the sheets without cutting the material, as shown in Figure 1.b. Technically, in both cases, the material of the sheets being joined is displaced, combined with local cutting or plastic deformation in the cold state. The joint formed without cutting is a more favorable variant of clinching because it has greater strength, as the fibers of the material are not interrupted during its formation but maintain a continuous flow following the geometric shape of the tool's working elements.


a)

b)

Figure 1. Schematic representation of clinching technology joining

The clinching method is carried out using special tools. The basic classification of clinching joining is done according to the kinematics of the tools, and in this sense, there are single-stage and multi-stage clinching. Unlike multi-stage tools, where joining occurs in several phases, in the single-stage system, the joint is created by applying pressure in a single working stroke. For this reason, this process is more commonly used in industrial applications.

The classification of the clinching joining system can also be made according to the shape or specifics of the tool's working elements. Systems with dies can be single-part, two-part, or multi-part, while the punch can be made according to TOX standards, cylindrical, concave, convex, etc. In the single-stage clinching process without a cutting part, the sheets are joined through localized cold forming using a special punch and die (mold). The punch presses and pushes the layers of material into the cavity of the die, creating local penetration. By applying pressure, the material is forced to flow sideways due to cold compression. The result of the process is an extruded button on the die side, which acts as the joint location, and a small, cylindrical cavity on the punch side. No finishing is required. In the simplest case of joining in one working stroke, a round conical punch and a cylindrical die with the shape shown in Figure 2. are used.

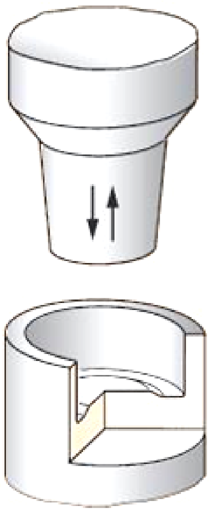


Figure 2. Tool working elements with a solid die

The topic of this work is related to the application of the TOX®-Clinching joining process, where the conical punch pushes the sheets toward the opening of the die. As the pressure force increases through the punch, the material of the sheets beneath the punch is forced to spread outward and fill the closed annular channel around the inner profile of the die. The result is an aesthetically pleasing round button, finely connected without sharp edges. The strong pressure exerted by the punch results in high holding forces on the joint location. An interesting question that arises in this process is how often the tool, or punch, needs to be replaced due to wear. In this regard, the research task of determining the minimum punch radius that meets the requirements for joint strength has been defined. If the radius wears below the minimum value, the required joint strength will not be achieved.

Using the methodology of planned experiments, regression analysis, and the Box-Behnken method, the value of the minimum punch radius was determined as shown below. For the purposes of the experiment, two different materials of varying thicknesses and the required joint strength force were defined.

2. PROCESS EXPLANATION

The pressure joining process can be used to join sheets of different qualities, surfaces, and thicknesses. This joining technique can be applied to various combinations of materials. Whether it's steel, aluminum, copper, brass, or stainless steel, it is also possible to join these materials together in various combinations. The pressure joining process provides the best electrical conductivity compared to other mechanical joining methods. This makes the method ideal for electrical assemblies and devices [2]. Although the joining process occurs in a single operation, several characteristic phases of joint formation are distinguished, as shown in Figure 3., a schematic representation of single-stage TOX clinching without local cutting with a movable upper punch and a one-piece die.

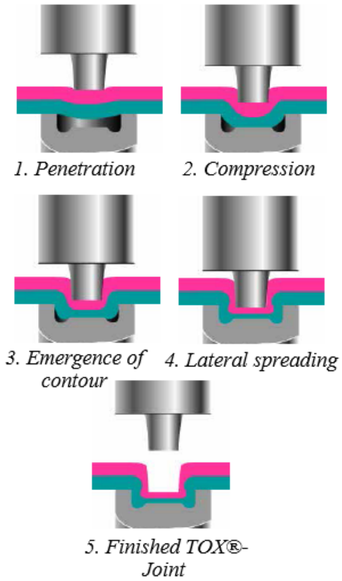


Figure 3. Steps of the pressure-based joining process [1]

These joints achieve high static forces, up to 70 % of the joint strength. They also exhibit a pronounced strain hardening effect, retain the surface coating, and are generally more cost-effective. Additionally, joining different materials can be achieved. Corrosion testing shows that the anticorrosive properties of the joined sheets, such as galvanization, remain intact since the surface coating is not damaged during the joining process. Otherwise, the surface of the sheets is not damaged by this deformation process, and the coating moves with the material and remains intact. Compared to spot welding, the clinching process does not have the negative effects of notch sensitivity. This ensures that the joint strength remains consistent throughout various load cycles [3]. In direct comparison to spot welding, the pressure joining process is approximately 40 % cheaper in terms of investment, operational costs, and tool costs. This is ensured by the following technical advantages:

- Reduced investment due to the long tool life,
- Low ongoing operational costs, as there is no need for additional material or elements,
- Rational production thanks to a high degree of automation,
- Energy savings, as no heat needs to be generated,
- No need for post-processing,
- Continuous quality control ensures verifiable quality [4].

The tools used are so-called piercing pins or punches, which have several characteristics and dies. The required tool set consists of: the pin, die, and sheet holder. The mechanical joining of two or more sheets is based exclusively on the precise movement of the pin into the die; the sheets are locally deformed without the use of any additional elements. The joint strength is the result of the material being locked in the shape of the letter "S." The quality of the process is strongly dependent on the precisely selected tools for the production itself [5]. Figure 4. shows examples of the working elements, i.e., punches and dies of some tools used for sheet joining.

Figure 4. Tool types [1]

3. MATERIAL SPECIFICATION AND PARAMETERS DEFINITION FOR EXPERIMENT

For the purposes of experimental research, two materials were used:

- DX54D + Z – 1.0306, galvanized deep drawing steel, with a thickness of 0,5 mm, and
- DX54D + ZM – 1.0952, with a thickness of 1 mm.

The chemical composition of these steels is presented in Table 1 and Table 2.

Table 1. Steel composition 1.0306 [6]

C	*Si*	*Mn*	*P*	*S*	*Cu*	*Ti*	*Al*
max 0,08	max 0,5	max 0,5	max 0,025	max 0,02	max 0,2	max 0,3	min 0,010

Table 2. Steel composition 1.0952 [7]

C	*Si*	*Mn*	*P*	*S*	*Cu*	*Ti*	*Al*
max 0,12	max 0,5	max 0,6	max 0,1	max 0,045	-	max 0,3	-

In the process of forming the joint location,
through extensive practical work and preliminary research, it was determined that three factors significantly affect the efficiency of the forming process:

- Punch radius,
- Piercing pressure,
- Penetration depth.

For the purposes of the experiment, the required force for achieving the joint strength, i.e., the force that the joint must withstand, was defined as 1,5 kN. Therefore, this is the key requirement that the joint must meet for the joint forming process to be considered efficient. In this regard, after the joining process was carried out, it was necessary to perform a quality control check of the joint location by testing the strength of the formed joint. Testing of the formed joint was conducted on a tensile machine, where the joined samples were stretched until the separation of the sheet components occurred, and the force was measured until the joint was fully separated.

4. EXPERIMENT CONDUCTING

The aim of the experiment is to establish a mathematical relationship between the above-mentioned factors and the output force for joint separation, i.e., joint strength. Referring to the Box-Behnken method for an experiment with 3 levels of factors and 15 experimental points, punches with 3 different radii were created. The required force should be F > 1,5 kN.
Through preliminary research, the influencing factors for achieving the required joint strength, i.e., holding force, which can be varied, were identified as:

- R - punch or pin radius [mm],
- P - piercing pressure [bar],
- h - penetration depth [mm].

Regression analysis should determine the relationship of force as a function of these influencing parameters, i.e.:

F = f (R, P, h).

The ultimate goal is actually to determine the minimum punch radius that achieves the holding force F = 1,5 kN, i.e.,

R_{min} = f (F, P, h), for F = 1,5 kN.

In this regard, the defined levels of influencing factors are given in Table 3., and the Box-Behnken matrix is shown in Table 4.

Table 3. Factors P,R, h levels

Influencing factors	Levels		
	-1	*0*	*1*
R (X1)	0,1	0,4	0,7
P (X2)	45	50	55
h (X3)	0,8	1	1,2

After conducting the experimental measurements of the separation force of the formed joints according to the experimental plan, the values of the separation force were entered in Table 5.

Table 4. Box-Bhenken matrix

Point	*R*	*P*	*h*
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Based on the data analysis performed using Data Analysis (Regression) in MS Excel, the characteristic values are presented in Table 6.

Table 5. Joint force measurements

Point	R	P	h	F [kN]
1	0,1	45	1	1
2	0,7	45	1	2
3	0,1	55	1	1,1
4	0,7	55	1	2,3
5	0,1	50	0,8	1,1
6	0,7	50	0,8	1,65
7	0,1	50	1,2	1,2
8	0,7	50	1,2	2,4
9	0,4	45	0,8	1,5
10	0,4	55	0,8	1,6
11	0,4	45	1,2	1,7
12	0,4	55	1,2	2
13	0,4	50	1	1,9
14	0,4	50	1	1,8
15	0,4	50	1	2

Table 6. Summary output from MS Excel

Regression Statistics	
Multiple R	0,92529785
R Square	0,8561761
Adjusted R Square	0,81695141
Standard Error	0,18713348
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	2,293125	0,764375	21,82747431	6,17E-05
Residual	11	0,38520833	0,03501894		
Total	14	2,67833333			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-0,88125	0,74651692	-1,1804823	0,262705651
R	1,64583333	0,22053892	7,46277946	1,25702E-05
P	0,02	0,01323234	1,51144901	0,158857114
h	0,90625	0,33080838	2,73950132	0,019248598

Through the analysis of the obtained values using regression analysis, the following conclusions can be drawn:

- The coefficient of determination R = 0,925 is satisfactory.
- Two significant factors are R and h, according to the P-value table for P < 0,05.

Based on this, an equation for the separation force of the joint F can be established:

$$F = 1{,}64 \times R + 0{,}906 \times h \qquad \text{... (1)}$$

From which the radius R can be determined:

$$R = \frac{F - 0.906 \times h}{1{,}64} \qquad \text{... (2)}$$

For the known value of the minimum force F = 1,5 kN and standard penetration depth h = 1 mm, the radius value is:

$$R = \frac{1{,}5 - 0{,}906 \times 1}{1{,}64} = 0{,}362\ mm \qquad \text{... (3)}$$

This result R = 0,362 mm represents the minimum radius required on the punch or pin in order to achieve a force of F = 1,5 kN.

The graphical representations in Figure 5 show the dependence of the significant factors on the response, i.e., the force F.

Based on the analysis of the diagrams in Figure 5, it can be concluded that a larger punch radius R and a greater penetration depth h have an effect on increasing the value of the force F.

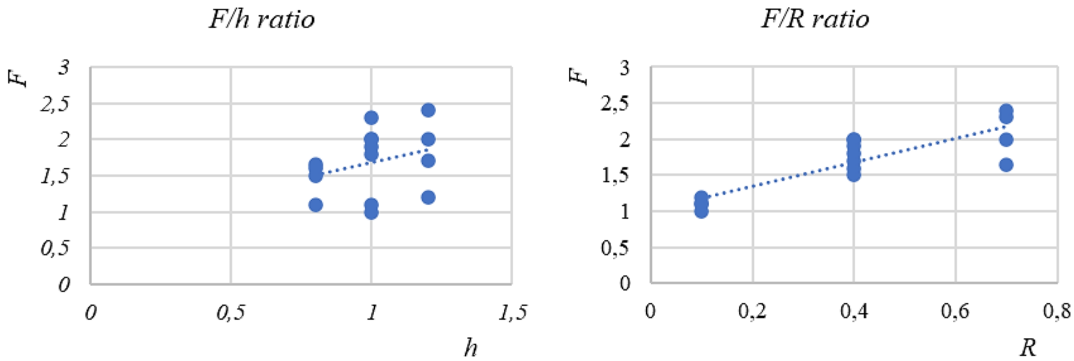


Figure 5. Significant factors h and R influence to response F

5. CONCLUSION

The joining by pressure process, or the "clinching" process, represents an interesting material joining technique that serves as a serious alternative to the electro-resistance spot welding process. With this method, different materials of varying thicknesses can be joined, including more than two materials at the same time. The process, unlike spot welding, is cleaner and faster. It does not generate any current or heat, and the safety aspects are better. On the other hand, the tools used are more durable than electrodes. The disadvantage of this process mainly relates to the higher investment in the machine as an initial cost, but this is paid off over the long term. This paper presents the application of the planned experiment methodology with the aim of determining the minimum punch radius for a predefined tear force between two joined materials in the joining by pressure process. For the realization of the planned experiment methodology, an experiment matrix was set up, and test specimens were created, which were then subjected to tearing tests, i.e., separation and measurement of the tearing force. Afterward, using MS Excel software and the Regression package, the dependencies between the input factors R, P, h and the output F were established, and the significant factors were identified. It was found that the most significant factor affecting the separation force of the joint was the punch radius R. This was assumed since preliminary research showed that the punch wears out during use, thus reducing its value. Therefore, this study and the applied scientific methodology aimed to calculate the minimum radius the pin must have in order to achieve the required tear force. By establishing a mathematical model based on the planned experiment and inputting the standard values of influencing factors in the sheet metal joining process, the minimum punch radius required to achieve the desired force value was calculated.

6. REFERENCES

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