Influence of tool geometry on reaction forces and strength of an inseparable joint produced on a prototype stand with the use of jaws

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Date: 2024-03-31T00:00:00+00:00

Abstract

The present article describes a new and innovative method of producing an inseparable joint with the use of expansion jaws. The effect of jaw tool geometry on the reaction forces and ultimate strength of an inseparable joint formed on a prototype stand was analyzed. The results are also compared of joints produced by jaws with single movement method and with complex movement method. The tool responds with bending and pressing one part into the other, which results in their permanent connection. In the tests, differentiation was introduced with regard to the height of the applied force to the collar of the connection pipe. A novelty is also a solution based on a complex, parameterized trajectory of the stamp movement consisting of horizontal and vertical displacements. This paper presents the tests of the joints formed at the stand. The new approach described in this article has resulted in a joint strength increase of approximately 30% using the innovative complex jaw movement of the biaxial clinching process. A joint tensile strength close to 1000 N was achieved.

Full Text

Preamble

Influence of Tool Geometry on Reaction Forces and Strength of an Inseparable Joint Produced on a Prototype Stand with the Use of Jaws

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Abstract

This article describes research on a new and innovative method for producing inseparable joints and testing their strength. The paper presents a novel approach to joint production using expansion jaws as a punch. The tool responds by bending and pressing one part into another, resulting in their permanent connection. The tests introduced differentiation in the height at which force was applied to the collar of the connection pipe. A further innovation is a solution based on a complex, parameterized trajectory of stamp movement consisting of horizontal and vertical displacements. This paper presents tests of joints formed at the experimental stand. The article also characterizes the produced joint through destructive testing: tensile strength tests. The new approach described herein resulted in approximately 30% increase in joint strength using the innovative complex jaw movement of the biaxial clinching process. A joint tensile strength close to 1000 N was achieved.

Keywords: Prototype stand, forces, fixed joints, non-detachable tight joints, crimp joints, folded joints, molded joints

1. Introduction

Inseparable connections used in industry for constructing components of automotive air-conditioning systems, internal combustion engine cooling systems, or cooling systems for batteries and heating systems powering electric vehicle engines and cabs require reliable connectors [1], [2]. It is essential to produce high-quality joints without defects [3], [4].

An important aspect is selecting the appropriate method for joining elements, which often depends on the available space for the operation [5], [6]. Joints made by clinching enable secure connection of two elements and allow joining various materials without corrosion risk [7]–[9]. This method uses an operation where two elements are geometrically combined through partial deformation caused by a punch and die [10]–[12]. The presented methods include both single-step and two-step processes, as described by various authors [13]. Another method involves kneading or forcing operations [14]. The advantage of these methods is that the surfaces of joined materials are not damaged, thereby limiting subsequent defects in final products [15], which affects product economy [16]. Despite different welding methods, aluminum alloy remains difficult to weld, especially thin-walled material [17]–[19]. Currently known methods include CMT welding and laser welding, which are still being developed to increase quality [20]. Other methods such as friction stir welding can also serve as alternatives [21], along with adhesive joining or mechanical crimping and clinching [22].

Han et al. [23] compared two different methods—Resistance Spot Welding and Self-Pierce Riveting—and concluded that the mechanical joining process was more stable than manufacturing inseparable joints through featured welding processes. Clinched and crimped joints can be treated as either intermediate solutions requiring additional technological operations or as final solutions. When treated as intermediate operations, subsequent gluing, welding, or soldering should be performed [24]. Producing inseparable connections requires transferring forces or moments to the connected system so it can withstand forces that would destroy the joint during subsequent technological operations or part usage. Salamati et al. [25] investigated various mechanical joining processes, covering principles of processing, applicable materials, process variants, and joint mechanical behavior including static and dynamic performance. Weber et al. [26] compared different processes for joining by forming of profiles, sheet, bulk, and sheet-bulk components, examining achievable joining mechanisms and significant process parameters influencing these mechanisms. Mori et al. [27] also analyzed joining processes including cold welding, friction stir welding, self-pierce riveting, mechanical clinching, and joining by forming. The process comparisons presented in these articles allow familiarization with joining methods used in industry and their advantages and disadvantages. Briskham et al. [28] investigated the best mechanical properties of joints manufactured by Self-Pierce Riveting, Resistance Spot Welding, and Spot Friction Joining, finding that the highest destructive force in studied cases was achieved by joints formed through mechanical deformation.

Developing methods to increase connection strength through two-axis complex clinching or crimping movement represents a new but highly desirable approach that should be developed for various industries, not only automotive and aviation. The joining method described herein was proposed by Rejek and other authors, who describe joining two components where walls are first folded and then pressed against each other [29].

After literature analysis, it was noted that no studies addressed clinched connections made through complex jaw movement. This is particularly important in cases where force must be applied in a relatively small space to produce a proper joint. The solution described below makes it possible to achieve greater connection strength using the same tool without requiring increased access at the jaw attack site.

2. Materials and Methods

The designed and manufactured tooling is capable of biaxial and parametric production of inseparable joints, dedicated to producing clinched, crimped, or bending joints. The connection is made by punches with a die, jaws, or cones. The investigated connection case before manufacturing is shown in Fig. 1 [Figure 1: see original paper].a, consisting of a pipe and connection pipe made of 6060 aluminum alloy, described in Tables 1 and 2 [30].

Table 1 . Chemical composition of aluminum alloy 6060 T4 according to EN-573-3:

Other Total 0,30- 0,10- 0,10 0,10 0,35- 0,05 0,15 0,10 0,05 0,15

Table 2 . Mechanical properties of aluminum alloy 6060 T4 in accordance with EN 755-2: 2008

Tensile strength Rm [MPa] Yield Elongation point A50mm % Rp0,2 [MPa]

The joint was designed to best match both elements while maintaining the possibility of manufacture through complex two-axis movement of the forming tool. In the described case, the joint was produced by expansion jaws with a new shape of forming surface. The lower edge of the tool is mapped above the intersection edge of the pipe and connection pipe shown in (Fig. 2 [Figure 2: see original paper].b).

Fig. 1. View of the pipe with connection pipe: a) joint components, b) marked edge to be mapped on tool.

To manufacture the tested connection between pipe and connection pipe, the forming jaws diverge in four directions for the vertical plane and one in the vertical direction according to the force of gravity. The joined parts must be pressed down during the crimping operation. The resulting joint strength also depends on part fit. The crimping method is schematically shown in three steps in Fig. 2. In the described case, the jaws were made of Inconel Vascomax C350 martensitic steel, allowing achievement of high loads. The tools were hardened to 58-60 HRC.

Fig. 2. Theoretical diagram of joint formation: 1st phase—before jaws enter (no contact with parts) (a); 2nd phase—contact with parts (b); 3rd phase—jaws entering material (c); 4th phase—vertical movement of jaws consistent with gravity force.

2.1. Stand and Socket Concept

Designing stands requires analysis of the functions the tooling or machine must fulfill. Concept considerations typically balance proper joint quality against machine and joint production cost.

A prototype stand was designed for joint production, with design granted patent number 426083 (22) 2018 06 26. The previously described joints were made at this stand, which is based on a plate-and-column structure. The stand design enables simultaneous work in two vertical axes, each equipped with a servo drive and external force sensor that monitors response forces achieved during joint production. Displacements generated by servomotors are measured with an optical encoder mounted in the motor. This solution enables parametric setting of the point where jaws attack the connection pipe. The zero point for jaw attack height is assumed at the mapping edge between pipe and connection pipe. This stand allows repeatable joint production and is flexible for adapting to parts of various dimensions.

The relatively small area where the desired force or torque should be applied to make the joint provides limited access for wedge application to the jaws. Wedge surfaces are responsible for transmitting vertical force to the jaw, which moves in the horizontal direction. The achieved transmission ratio in the system is 1:19.

Figure 3 [**Figure 3: see original paper**] shows the station view with actuator and sensor elements.

Servo motors from Beckhoff were used as actuators, with nominal torque of 10 Nm and speed of 2300 rpm. The sensory and measurement systems are based on the following elements: - CL 16m 30kN force sensor with CL 10D 4-20mA transducer and 0.5% resolution - CL 21RS 30kN force sensor with CL 10D 4-20mA transducer and 0.5% resolution

To collect results, a PC with PLC was used. This system collects 4-20 mA current signals from force sensors and two 18-bit optical encoders responsible for tracking jaw displacement. The joint was manufactured using specially designed tooling that allows proper transfer of necessary forces to produce the joint. The tooling is also designed for biaxial force application, enabling control of jaws in horizontal X and Y axes and vertical Z axis for the entire system (Fig. 3).

Fig. 3. Stand view used in joint production; view of tooling for making joints.

2.2. Methodology of the Experiment

Eighteen sets of parts were produced for testing. The experiment was prepared using samples characterized by one set of diameters. The research goal was to identify parameters yielding maximum tensile strength of the joint. The joint cross-section in 3D view is shown in Figure 4 [Figure 4: see original paper] with measurement data in Table 3 .

Fig. 4. Joint view with characteristic dimensions.

Table 3. Measurement result of the joint ØB [mm] 30 h11

13 H8/h7

Joint preparation used one set of jaws with a forming surface featuring vertical grooves for crimping. The jaws were divided into two groups—high and low—

to best reflect the inner edge of the tube opening. The experiment was divided into two main groups based on jaw position, relating to the attacking height of jaws on the connection pipe collar noted as "LP" shown in Fig. 5 [Figure 5: see original paper]. Tests examined two jaw attack heights on the collar: "00" where distance LP is 5 mm, and "+05" where LP is 5.5 mm, representing a 0.5 mm difference in force application.

Fig. 5. View of forming jaws for manufacturing the joint.

Motion was also diversified. Joints were made with single movement of forming jaws (diverging only horizontally in 4 directions) and with complex movement where jaws, after horizontal movement, performed downward working movements of 0.3 mm and 0.5 mm (Table 4).

Table 4. Design of experiment.

Joints were manufactured under constant sensor control using displacement and force sensors. Results are represented by graphs showing exact reaction forces needed to produce each joint. Manufactured samples were subjected to tensile strength testing on the same stand used for joint formation monitoring. To perform tests, internal threads were made in connection pipes while pipes were gripped by a socket with mapped pipe shape.

3. FEA Analysis

Finite element analysis was performed for all samples presented in Table 4 using Solidworks Simulation software with nonlinear material capability. This approach enables determination of optimal forming tool shapes without costly and time-consuming physical tests. Due to the axisymmetric nature of the sample, analysis was conducted on one quarter, reducing calculation elements while increasing accuracy. The material used for analyzed parts was 6060 T4 aluminum, for which a strength curve shown in Fig. 6 [Figure 6: see original paper] was created and implemented in the program as a calculation model.

Fig. 6. Stress-Strain Curve for aluminum 6060 T4.

The program automatically retrieves all information from the graph except Poisson's ratio, which was set at 0.33. The established model for sample calculations is the Von Mises method, which is most appropriate for this test type, with the plot starting at assumed yield strength to render parts nonlinear. The program calculates steps using the formula below:

The jaw material analyzed in the program is K490, with values given in Table 5 . Since the jaws themselves were not tested, they were considered rigid to avoid interfering with analysis results. Simulation duration was 1 or 2 seconds depending on movement count: 1 s for single movement, and 2 s for double movement (horizontal movement for 1 s, then vertical movement for 1 s). The Newton-Raphson iteration method was adopted.

The contact iterations used for testing are shown in Fig. 7 [Figure 7: see original paper].a, Fig. 7.b, and Fig. 7.c, describing possible contact between assembly parts. Degrees of freedom in test sample space were also limited according to actual test conditions (Fig. 7.d). The friction coefficient was set at 0.05.

Table 5. Properties of K490 material used for jaws.

Properties of steel K490: Chemical composition C [%] Cr [%] Mo [%] V [%] W [%] Nb [%] Mechanical properties 0,28 2436

Fig. 7. Fixing in space and contact interactions of the FEM model: a), b), c) contact iterations, d) considered degrees of freedom.

Mesh data and the mesh plotted on the model are shown in Fig. 8 [Figure 8: see original paper]. The model was divided into a 1.5 mm mesh with refinement to 0.5 mm in the deformed area, resulting in 10,540 elements analyzed.

Fig. 8. Mesh on analysis parts and mesh properties during FEA.

Results for all analyses are presented in Table 7 . The results align with expectations and correspond to implemented displacement, confirming correct analysis execution. Fig. 9 [Figure 9: see original paper] shows sample behavior after reaching assumed displacement and where maximum stresses—and thus forces necessary for desired deformation—can be expected. This analysis approach easily determines optimal tool shape and identifies displacement values beyond which sample damage occurs.

Table 7. Result of analyzed samples.

Fig. 9. Visualization of deformation on Solidworks.

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4. Results and Discussion

Research analyzed two different joint production methods with varying parameter values characterizing each method. All cases used the same forming jaw type to produce fixed connections of two parts.

In the first case, the parameter defining force application height was 5.5 mm ("+05"), while the parameter characterizing jaw movement was 0.3 mm. Radial movement speed was 1.83 mm/s. Reaction forces recorded on the flat cylinder sensor reached a maximum vertical axis value of 1.1 kN, which converted to radial movement equals 21.05 kN for all 4 jaws (Fig. 10 [Figure 10: see original paper].a). The tested joint strength was 307 N at joint destruction (Fig. 10.b).

Fig. 10. Obtained data for joint produced by jaws with single movement, height LP "+05" , forming jaw movement 0.3 mm: a) reaction force values, b) joint strength in tensile test.

The second case involved manufacturing with complex motion in two stages. The first phase had vertical downward movement of 0.1 mm at 35 mm/s speed.

Second displacement additionally formed material and increased joint strength. The first force increase stage was slightly higher than the previously described group, reaching 23.24 kN. A force decrease was observed for the second stage, which may be attributed to the beginning of vertical movement and force increase on the ring sensor (Fig. 11 [Figure 11: see original paper].a). Manufacturing the joint using complex movement increased strength, with connection failure occurring at 408 N (Fig. 11.b).

Fig. 11. Obtained data for joint produced by jaws with single movement, height LP "+05" , forming jaw movement 0.3 mm and vertical movement 0.1 mm: a) reaction force values, b) joint strength in tensile test.

The third case concerned a joint made with single movement, force application height parameter of 5.5 mm ("+05"), and jaw distance parameter of 0.5 mm per side. Radial movement speed was 1.83 mm/s. Reaction forces registered on the sensor reached maximum vertical axis value of 1.17 kN, converting to 22.41 kN radial movement for all 4 jaws (Fig. 12 [Figure 12: see original paper].a). The tested joint strength reached 599 N before higher forces destroyed the joint (Fig. 12.b).

Fig. 12. Obtained data for joint produced by jaws with single movement, height LP "+05" , forming jaw movement 0.5 mm: a) reaction force values, b) joint strength in tensile test.

The fourth case tested joint production with force application height parameter of 5.5 mm ("+05") and jaw distance parameter of 0.5 mm using complex motion. In the second movement phase, jaws made 0.2 mm vertical downward movement at 35 mm/s speed. The first force increase stage was higher than previously described groups at 26.50 kN, then force decrease was observed indicating vertical movement beginning and force increase on the external ring sensor (Fig. 13 [Figure 13: see original paper].a). The compound movement increased joint strength, which did not deteriorate until 925 N (Fig. 13.b).

Fig. 13. Obtained data for joint produced by jaws with single movement, height LP "+05" , forming jaw movement 0.5 mm and vertical movement 0.2 mm: a) reaction force values, b) joint strength in tensile test.

The fifth case concerned a joint made with straight movement, force application height parameter of 5.0 mm ("+00"), and jaw spreading distance of 0.5 mm. Radial movement speed was 1.83 mm/s. Reaction forces recorded on the "button" sensor reached maximum vertical axis value of 1.60 kN, converting to 30.67 kN for all 4 jaws (Fig. 14 [Figure 14: see original paper].a). The tested joint experienced complete failure at 810 N (Fig. 14.b).

Fig. 14. Obtained data for joint produced by jaws with single movement, height LP "+00" , forming jaw movement 0.5 mm: a) reaction force values, b) joint strength in tensile test.

The final case concerned joint production with force application height parameter of 5.0 mm ("+00") and jaw spreading distance of 0.5 mm using compound motion. In the second movement phase, jaws made 0.1 mm vertical downward movement at 35 mm/s speed. The first force increase stage was similar to previously described groups at 30.79 kN, then force decrease was observed indicating vertical movement beginning and force increase on the external ring sensor (Fig. 15 [Figure 15: see original paper].a). The completed motion increased joint strength, which did not deteriorate until 1014 N (Fig. 15.b).

Fig. 15. Obtained data for joint produced by jaws with single movement, height LP "+00" , forming jaw movement 0.5 mm and vertical movement 0.1 mm: a) reaction force values, b) joint strength in tensile test.

Summarizing resultant reaction forces and joint strengths produced with the same spreading jaws using different parameters characterizing joint production methods revealed the influence of applied force magnitude on resulting reaction forces and joint strength. For the first case using the basic method, the lowest reaction forces were observed, but joint strength was also lowest among tested cases. For the second case with 10% increased reaction forces and complex jaw movement, a 33% joint strength increase was noted. Further tests increased the jaw spreading distance parameter from 0.3 mm to 0.5 mm, which for straight jaw movement resulted in 6% higher reaction forces compared to the first case and 95% higher joint strength. The fourth case used complex jaw movement with parameters of 0.5 mm horizontal movement and 0.2 mm vertical movement, producing 18% higher reaction forces and 54% higher joint strength compared to the third case. Relative to the first case, this represented 26% increased reaction forces with simultaneous 201% joint strength increase.

Subsequent cases investigated LP parameter influence on reaction forces during joint production and joint strength. Compared to previous cases, force application height was changed from 5.5 mm to 5.0 mm, resulting in 37% higher reaction forces and 35% higher joint strength compared to the third case. Relative to the base case, reaction forces increased 46% while joint strength increased 264%. For complex motion with LP parameter "00" (5.0 mm force application height) and 0.1 mm vertical movement, reaction forces increased 16% and joint strength increased 10% compared to the fourth case. Relative to the first case, reaction forces increased 46% and joint strength increased 230%. Research results are presented in Table 8 .

Table 8. Comparison of obtained reaction forces during joint production and joint strengths in tensile tests depending on process parameters.

"+0,5" ; "+0,5" ; "+0,5" ; "+0,5" ; "+0,0" ; "+0,0" ; sjh=0,3; sjh =0,3; sjh =0,5; sjh =0,5; sjh =0,5; sjh =0,5; sjv=0; sjv=0,1; sjv=0; sjv =0,2; sjv=0; sjv =0,1; Reaction forces during the production of the joint [kN] Strength of joints in a tensile test [kN]

Analysis shows that joint strength and required reaction forces are influenced by distance LP, which affects the angle formed between the rivet flange wall and the inner edge of the hole in the pipe. Fixed joints are divided according to their implementation purpose: the first group for intermediate connections and the second for final connections. This division distinguishes whether further operations are necessary for the element combination to meet requirements. The presented diagrams enable tracking joint formation and full process control. Solidworks simulation results reflect data recorded during actual testing. Discrepancies when comparing the two graphs may result from force absorption by jaws and intermediate parts due to their deformation, which are not considered in FEA analysis and may cause differences. However, simulation effectively provides full preview of deformations that reflect reality.

6. Conclusions

The conducted analyses and tests demonstrate that the new joint production method based on complex jaw movement effectively increases joint strength. The performed studies allow formulation of the following conclusions:

1. The height difference between the force application point and jaw attack point is 0.5 mm, representing 10% difference relative to the Lp parameter. Energy consumption for joint forming force in case 1 was 10% lower than in case 2 using complex motion. Joint 2 produced by two-axis jaw movement increased joint strength by 33% compared to case 1, achieving force exceeding 400 N.

2. The ratio of joint strength to required production forces in cases 1 and 2 was only 1% higher for complex motion. Energy consumption for joint forming force in case 4 was over 18% greater than in case 3 using complex motion. Joint 4 produced by two-axis jaw movement increased joint strength by more than 50% compared to case 5, achieving force over 920 N.

3. The ratio of joint strength to required forces in cases 3 and 4 was 3% for both tests. Energy consumption for joint forming force in case 5 was 1% lower than in case 6 using complex motion, proving that at low Lp parameter values, jaws may slip during vertical movement.

4. Joint 6 produced using two-axis jaw movement increased joint strength by 25% compared to case 5, achieving force exceeding 1000 N. The ratio of joint strength to required forces in cases 5 and 6 was 3% for both tests.

5. The greatest joint strength was achieved in case 6; however, the highest percentage force increase occurred in case 4, which was over 50% compared to case 3.

The machine is equipped with two servo systems and external force and displacement measurement systems, providing full process control capability. Finite element analysis in Solidworks Simulation can effectively compare methods or forming tool shapes.

6. Comparing reaction force graphs from actual tests to FEA tests shows result reflection.

Funding: This research was funded by [Regional Operational Programme for the Wielkopolska Voivodeship financed by the Structural Funds of the European Union and the State budget of Poland] grant number [RPWP.01.02.00-30-0046/16]. The research leading to these results received funding from the Norwegian Financial Mechanism 2014-2021 under Project Contract No 2020/37/K/ST8/02748.

Conflict of Interests: The authors declare no conflict of interests regarding publication of this article.

Data Availability: All data producing results in this work can be requested from the corresponding author.

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[30] "ALUMINIUM-ALLOY-EN-AW-6060_{MATERIAL}-DATA-SHEET_{ALUMINCO}" .

Note: Figure translations are in progress. See original paper for figures.

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