Journal of Materials Processing Technology 230 (2016) 109–120

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Damage analysis in mechanical clinching: Experimental and numerical study

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ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 26 October 2015
Accepted 15 November 2015
Available online 2 December 2015

Keywords:
Mechanical joining
Clinching
Damage
FEM
Aluminium alloy
Thin sheets
Numerical model
Ductility
Formability
Failure analysis

ABSTRACT

A numerical model describing the evolution of ductile damage was developed to predict the onset of fracture during the clinch joining of thin aluminium AA6082-T6 sheets. The damage model was calibrated and validated using instrumented punch-out tests in order to increase the reliability and robustness of the damage parameter. An inverse analysis was performed (by varying the damage parameter) by minimizing the difference between the experimental and numerical prediction concerning the load-stroke curves and the geometries of punched cross-sections. Then, a numerical model of mechanical clinching using the damage parameter was developed and compared with experimental clinched connections. The results show that the model enables the onset of cracks in critical regions to be predicted. The critical regions are the punch-sided sheet neck and die-sided sheet bulge. The established numerical model of clinching provides a viable means for optimizing the geometry of the clinching tools so as to improve the mechanical behaviour of the joints (by maximizing the undercut and reducing the neck thinning) other than preventing the onset of cracks on the joints.

1. Introduction

Transportation, automotive and aerospace companies are seeking to employ new high performing materials as a means for increasing the energy efficiency of their products. Many of these new materials (e.g. metal alloys, polymers and fibre reinforced plastics) are difficult to join using traditional methods such as welding.

Fast mechanical joining processes such as Self-Pierce Riveting (SPR) and Mechanical Clinching (MC) represent viable solutions to meet the above-mentioned requirements. Because they are mechanical joining processes, they do not require the surfaces to be specially prepared and they can be successfully employed even on pre-painted sheets. The difference in the thermal and physical properties of the sheets being joined is less restrictive than for adhesive bonding or welding processes. Finally, SPR and MC do not require pre-drilled holes. This greatly decreases the joining time and cost by eliminating the drilling step needed in conventional riveting processes. Mechanical clinching offers the additional advantage of not requiring an external component (such as the rivet used in SPR). This results in a lower cost per joint, weight saving, lower forming force and avoids the galvanic corrosion that can occur in joints formed by using SPR (Calabrese et al., 2015). Mechanical clinching employs relatively simple equipment consisting of a clinching gun (which may even be portable), a punch and a die. The sheets being joined are overlapped and are plastically deformed by driving the punch against the sheets to produce an undercut that fastens the sheets. The formation of the undercut is controlled by the die, the shape of which determines the material flow during the joining process. An ample literature has been produced on clinching of steel and aluminium sheets driven by the growing interest from automotive industries. Mucha and Witkowski (2014) performed an experimental investigation on the change in mechanical behaviour of clinched connections loaded in different directions. Abe et al. (2014) studied the suitability of clinching for joining high-strength steel alloys. Lambiase and Di Ilio (2014) compared the shear and peeling behaviour of clinched joints performed with different tools on low carbon steel. Jiang et al. (2014b) developed a non-destructive monitor method for inspecting the strength of clinched connections performed on aluminium alloys. Jiang et al. (2014a) also investigated the effect of pre-straining when joining aluminium and steel alloys. The use of clinch join-

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http://dx.doi.org/10.1016/j.jmatprotec.2015.11.013
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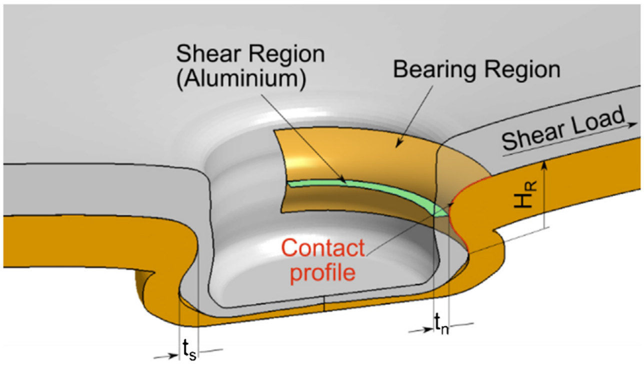

Fig. 1. Main characteristic dimension of clinched connections.

ing has been extended to a wider range of materials because of the advantages described above. He et al. (2015) employed external pre-heating (using a flame heating) to increase the formability of the material and consequently to join different titanium alloys using extensible dies. Lambiase (2015b) and Lambiase and Di Ilio (2015) studied the feasibility of the clinching process to produce hybrid metal-polymer joints and studied the mechanical characteristics and process conditions required for the thermoplastics to be joined to aluminium by clinching, Lee et al. (2014) studied the suitability of hole-clinching for joining aluminium and steel sheets with carbon fibre reinforced plastics.

In the above-mentioned researches, one of the main problems while joining new materials by clinching was represented by the metal formability. To this end, two possible ways can be followed: increasing the material formability by pre-heating either improving the material flow (by optimizing the geometry of the clinching tools) to prevent onset of cracks. Pre-heating may complicate the process, increase the processing time, cause microstructural changes (such as increase in grain dimensions) either change the mechanical behaviour of the joints. On the other hand, the optimization of the material flow, which could be more effective, requires extensive experimentations. A possible solution is represented by the employment of numerical models involving damage evolution during clinch joining. He (2010) performed a literature review concerning the recent developments in FE models for studying the clinching process. The influence of process parameters on neck thickness and the undercut have been deeply investigated to improve the joint quality. He et al. (2014) developed a FE model of clinching to analyse the shear behaviour of clinched connections and the material flow. The advantages of the numerical models of clinch joining state in the possibility to determine the effect of process conditions on the material flow, main dimensions and the distribution of stresses in joints. Nevertheless, accurate calibration of these models (e.g. flow stress, friction model, etc.) is required to develop a reliable model.

So far any of the proposed model was aimed at predicting and preventing the onset of cracks during clinch joining, which can dramatically affect the static and dynamic mechanical behaviour of the joints. Zhao et al. (2014) developed a FE model using damage criteria to predict the mechanical behaviour of clinched connections during single lap shear tests. Xu et al. (2014) developed a numerical model for predicting the failure behaviour of the clinched joint on AA6061 alloy. Bouchard and co-workers involved damage modelling to predict the mechanical behaviour of self-pierce riveted and clinched joints. Bouchard et al. (2008) performed an accurate model calibration for simulating SPR process using a 2D axisymmetric model. The stress, strain and damage fields were then mapped on a 3D model in order to simulate a shear test. It was found that, the developed model predicted with good accuracy the experimental shearing strength. In a subsequent work, Roux and Bouchard (2013) employed a similar approach to maximize the tensile strength of clinched joints and optimized the clinching tools by means of a numerical model involving a damage criterion. Nevertheless, the Authors did not focus on the stress developing during the clinching process which leads to material damage as well as they did not discuss the conditions causing unsuccessful clinch joining owing to fracture development in the sheets.

The present work is aimed at analysing the stress developing during clinch joining which cause material fractures and how the clinching tools geometry influence such stress and damage evolution. To this end a numerical model of mechanical clinching involving Rice and Tracey's damage criterion was developed. A calibration procedure based on inverse analysis was carried out to determine the critical damage parameter. The procedure was based on the comparison of the experimental load-stroke curves and geometries with numerical predictions in punch-out tests. In order to increase the robustness of the inverse analysis, different processing conditions were tested, i.e. varying the punch-die clearance. Once the correct value of the damage parameter was determined, a finite element model of the clinching process involving the damage criterion was carried out. The results of the numerical model were compared with the experimental findings, varying the geometry of the punch and the die. Fractography analysis was also performed to verify whether the developed model was capable to predict the fracture propagation paths shown by clinched connections during the joining process. A good agreement between the experimental cross sections of the joints with numerical predictions was found.

2. Fractured regions in clinched connections

Israel et al. (2013) identified the main phases in which the clinch joining develops, namely: offsetting, upsetting and flow pressing. During the offsetting phase, the punch stretches the two sheets within the die cavity. The strain is concentrated around the punch corner because the punch (and die) fillet radius is reduced by the sheet thickness ratio. Mucha (2011) reported that increasing the

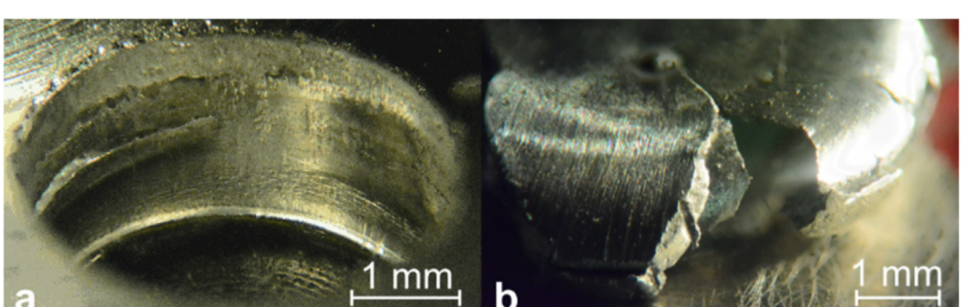

Fig. 2. (a) Fracture at the punch-sided sheet and (b) Fracture at the die sided sheet (radial crack).