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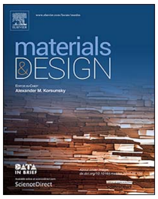

Process-induced bottom defects in clinch forming: Simulation and effect on the structural integrity of single shear lap specimens

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ABSTRACT

Lightweight and high strength sheet metal such as aluminum alloy sheets are used in a variety of industrial applications. Due to the limited weldability of these materials, mechanical joining techniques such as clinching are of interest. The challenge in this regard is that conventional round clinch forming locally induces large plastic deformations which potentially cannot be accommodated by materials with limited ductility. Ductile damage models are used to predict the occurrence of bottom cracks during conventional round clinch forming of EN AW-6082 T6 sheet. It is shown that cracks in the bottom of a clinched joint and the final static strength of a single lap shear specimen can be numerically reproduced provided that the post-necking strain hardening behavior and damage behavior of the base material are properly identified. The observed bottom cracks did not have a detrimental effect on the static strength and fatigue life of single shear lap specimens. It is hypothesized that fatigue cracks in single shear lap tests initiate due to fretting.

1. Introduction

Materials with high specific strength (lightweight and high strength) but with limited ductility have entered a variety of industrial applications. For example, the use of aluminum alloy sheets and die castings has increased significantly in automotive applications [1]. Due to the limited weldability, joining these materials by mechanical joining techniques such as clinching is of interest. The basic principle of clinch forming processes is to create an interlock between the combining thin metal parts with the aid of relatively simple tools like a punch, a blank holder and a die [2]. The punch locally pushes metal into the die and, depending on the shape of these clinching tools, the resulting metal flow targets the creation of a permanent mechanical interlock. Depending on the application rectangular or round clinching tools are used. Materials with limited ductility, however, are conventionally clinched using rectangular clinching tools [3] which partially shear the sheets forcing the top sheet through slits at the bottom sheet, see Fig. 1. As such, shear clinching technology [4] yields a joint with sharp edges which have a detrimental effect on the fatigue life of the joint [5]. Additionally, the perforated sheets are prone to corrosion. For these reasons, conventional round clinching is usually preferred in industry yielding symmetrical load-bearing joints with a superior fatigue strength [3].

The challenge in this regard, however, is that conventional round clinch forming locally induces very large plastic deformations which can cause ductile fracture and cracks [6], significant local microstructural changes [7] and characteristic residual stress fields [8]. Obviously, these effects could potentially affect the in service structural integrity of the joint.

Since clinching solely relies on plastic deformation of the base materials, a certain amount of ductility is required for obtaining defect-free joints. Early assessment of *clinchability* for materials was based on a 180 ° bending test with zero radius [9]. Varis [10] formulated guidelines to assess the clinchability of materials as function of material parameters. Based on the available data on conventional clinching of high strength steels in 1998, Varis found that materials can be clinched provided that the elongation at break $A_{80} \geq 10\%$ and the proof stress $\sigma_{0.2} < 550$ MPa. A more recent guideline [11], however, recommends to consider both the elongation at break $A_{80} \geq 8\%$ and the strength-related metric $\frac{\sigma_{0.2}}{\sigma_{UTS}} \leq 0.7$. The latter ratio of proof stress to ultimate tensile strength enables to include the effect of strain hardening of the base material. The implication of these guidelines on commercial available aluminum alloys can be visualized using a so-called Ashby-diagram [12], see Fig. 2. Each bubble in this chart represents a member of the aluminum alloy family (here 279 records). The vertical axis shows the elongation at break A_{80} (i.e. a ductility metric) and the horizontal axis shows the strength-related metric $\frac{\sigma_{0.2}}{\sigma_{UTS}}$. The guidelines for clinchability [11] are shown in this chart as black solid lines

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Nomenclature

A_{80}	Elongation at break
$\sigma_{0.2}$	Proof stress
σ_{UTS}	Ultimate tensile strength
K_{bh}	Stiffness blank holder
X	Bottom thickness
t_n	Neck thickness
t_u	Interlock
μ_i	Coulomb friction coefficient
σ_y	Yield stress
$\tau_{\max}$	Shear stress limit
σ_{ref}	Equivalent stress
K	Strength coefficient
ϵ_0	Pre-strain
ϵ_{eq}^{pl}	Plastic equivalent strain
n	Strain hardening exponent
$\dot{\epsilon}$	von Mises strain rate
m	Strain rate sensitivity
r	Lankford ratio
$\epsilon_{\max}$	Maximum uniform strain
$\sigma_{\max}$	Equivalent stress at maximum uniform strain
ϵ_R	Fracture strain
σ_1	Maximum principal stress
σ_{eq}	Equivalent stress
σ_H	Hydrostatic stress
f_0	Initial void volume fraction
k_ω	Shear damage parameter
f_c	Critical void volume fraction
f_g	Void volume fraction in the bottom of the clinched joint
f_n	Void volume fraction in the neck of the clinched joint
L_0	Initial gauge length extensometer
R	Force ratio in cyclic single shear lap testing

dividing the chart in two distinct regions: *good clinchability* and *process-induced defects*. It can be seen from Fig. 2 that 62 (purple bubbles) out of 279 commercial available materials can clinched without generating forming defects. High strength aluminum alloys are clearly prone to process-induced defects in clinch forming.

In this paper clinch forming of EN-AW 6082-T6 is under investigation. The material is labelled in Fig. 2 showing that it is prone to process-induced defects. The latter is confirmed in a recent study of Lambiase and Di Illio [6].

The most obvious solution for this problem is to increase the ductility of the base material by proper heat treatment or thermally supported clinch forming. Various methods have been proposed for heating up the substrates [13–15]. The option of heating up the tools is investigated by Hübner [14]. Hahn et al.[13] proposed an alternative method based on electromagnetic induction. He et al. [15] used flame heating to increase clinchability of titanium alloys. Recently Zhang et al. [16] investigated the effects of post-heat treatments (annealing and quenching) on the fatigue performance of clinched titanium alloy joints. Lambiase [17] recently showed that EN-AW 6082-T6 sheet can be clinched without the formation of cracks if the material is pre-heated adequately. Obviously, specific (local) heat treatments or thermally supported clinching complicate the manufacturing sequence resulting in higher costs and therefore cold clinching is usually preferred in industry.

A second solution to avoid process-induced defects is by modifying the geometry of conventional clinching tools. Such adaptive design is usually driven by numerical simulations. The majority of the published work on numerical simulation of clinched joints, however, deals with the study of the joint quality (i.e. shape and interlock) [18,19] and the associated final quasi-static strength [20–24]. Obviously, these studies are important to understand the impact of the clinching tools on the metal flow and the resulting interlock and neck thickness, and, consequently the final strength of the joint. Less attention, however, went to numerical optimization of clinching tools to avoid specific process-induced clinch forming defects. Neugebauer et al. [25] proposed dieless clinching to minimize crack-inducing tensile stresses. Abe et al. [26] modified a conventional clinching die with the aid of finite element techniques to obtain a defect-free joint between high strength steel and aluminum alloy sheet. Behrens et al. [27] used Oyane's damage criterion to optimize clinching tools and minimize damage in die cast aluminum alloy. Lambiase et al. [28] found that shallow dies and punches with smoother fillet radii enable to prevent cracks during clinching of aluminium alloys. A recent study of Lambiase [6] aimed at acquiring an improved understanding of the conditions causing process-induced defects in conventional clinch forming of materials with limited ductility. Lambiase inversely calibrated Rice and Tracey's

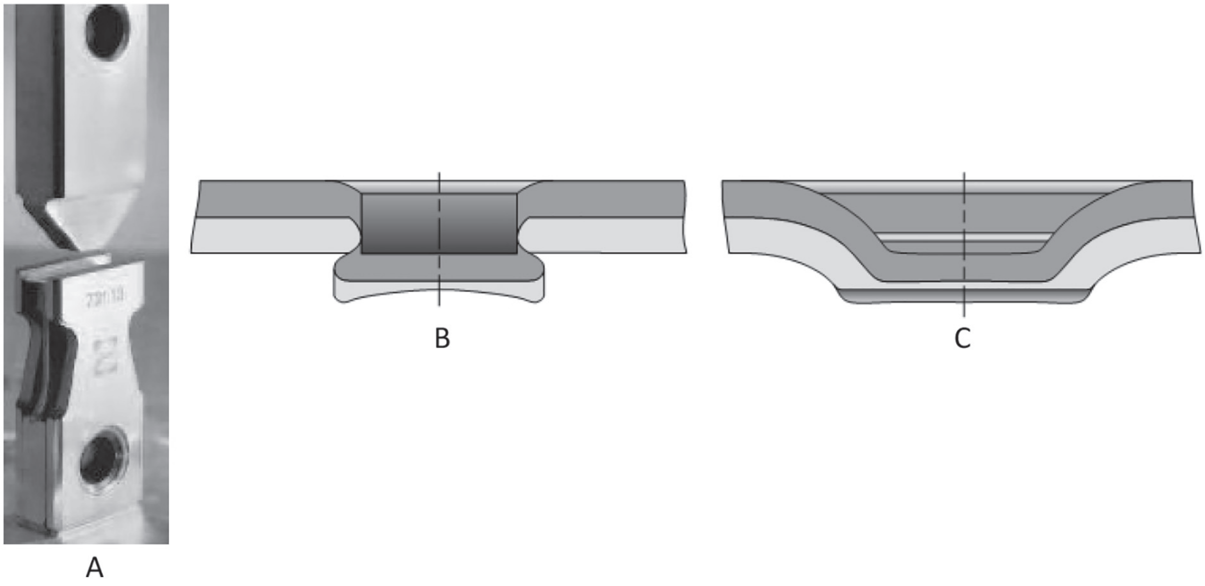

Fig. 1. A. Rectangular clinching tools. B. Cross-section front view. C. Cross-section side view.