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Internal ductile failure mechanisms in steel cold heading process

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ABSTRACT

The occurrence of internal ductile failure in cold-headed products presents a major obstacle in the fast expanding cold heading (CH) industry. This internal failure may lead to catastrophic brittle fracture under tensile loads despite the ductile nature of the material. Comprehensive testing and investigation methodologies were used to this work to reveal the complicated interplay of process and material parameters contributing in the initiation and propagation of internal ductile failure in six CH quality AISI steel grades.

The metallurgical and microscopic investigations showed that internal ductile failure occurs progressively by void nucleation and growth mechanisms with increasing plastic strain inside the highly localized adiabatic shear bands (ASBs). The void nucleation occurs by decohesion at second-phase particles, inclusion–matrix interfaces, grain boundaries and by particle or inclusion cracking. Therefore, the number and morphology of any inclusions and second-phase particles are key factors in material formability.

The metallurgical investigations showed that under compressive loading conditions, the nature of the metal flow pattern promotes different rates of material flow around the inclusions and stringers which supports decohesion and void nucleation since the early stages of deformation. At advanced stages of deformation, the metal flow pattern contributes to the ASB localization in supporting void growth and coalescence along the band leading to narrow void sheets.

All tested materials in this work experienced ductile failure by void nucleation and coalescence, forming cracks along the ASBs. The ductile failure of each material was the result of the contribution of all the mechanisms of void nucleation at the inclusion–matrix interface, second phase–matrix interface and at the grain boundaries. However, the level of contribution of each mechanism in the final ductile failure varied depending on material properties and their microstructure.

1. Introduction

The occurrence of any failure is a major limitation governing the limits of any forming process. Therefore, understanding the failure mechanisms and the complex interplay of process and material parameters in the failure occurrence in metal forming operations has attracted the attention of many researchers for more than six decades. The knowledge of different failure mechanisms is crucial to improve product quality and design methodologies.

Barrett (1997) considered in his report about the fasteners that the cold heading (CH) process is one of the most important multi-stage metal forming processes because of its many advantages over machining of the same part, including high productivity for complex final shapes, minimum material waste and increased tensile strength from cold working. Chitkara and Bhutta (2001) who studied the near-net shape heading of splines and solid spur gear forms reported that the decision to use the CH process to manufacture certain products depends on the complexity in the shape of the head and the material employed and the possibility of internal and external failure occurrence.

Currently, the CH industry favors using faster headers, reducing the number of manufacturing stages, and producing high-strength fasteners without final heat treatment. To achieve these goals, modified process designs are required which result in higher strains and strain rates, which cause two familiar types of ductile defects in the cold-headed products. The first is the external oblique or longitudinal crack caused by the exhaustion of the material ductility. The second failure was reported by Bai and Dodd (1992) in their study for the adiabatic shear band (ASB) phenomenon. They reported that the ASBs may lead to internal crack. Okamoto et al. (1973) stated in their study of different forming processes that this type of failure may result in splitting of the fasteners' heads as shown in Figs. 1–3, respectively.

Many researchers have focused on surface defects. Cockroft and Latham (1968) and Lee and Kuhn (1973) studied this defect in upsetting and presented different criteria to predict it. Nickoletopoulos

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(2000) studied the surface defect in CH process and reached to a conclusion that Cockroft–Latham criterion can be used to predict the surface defect in CH process with a reasonable accuracy. In addition to the large number of studies that covered this type of failure extensively, it can be visually inspected and accounted for in the process design of the component for removal by means of machining or trimming. Thus far, internal ductile failure due to the ASB phenomenon in CH process has not received the same atten-

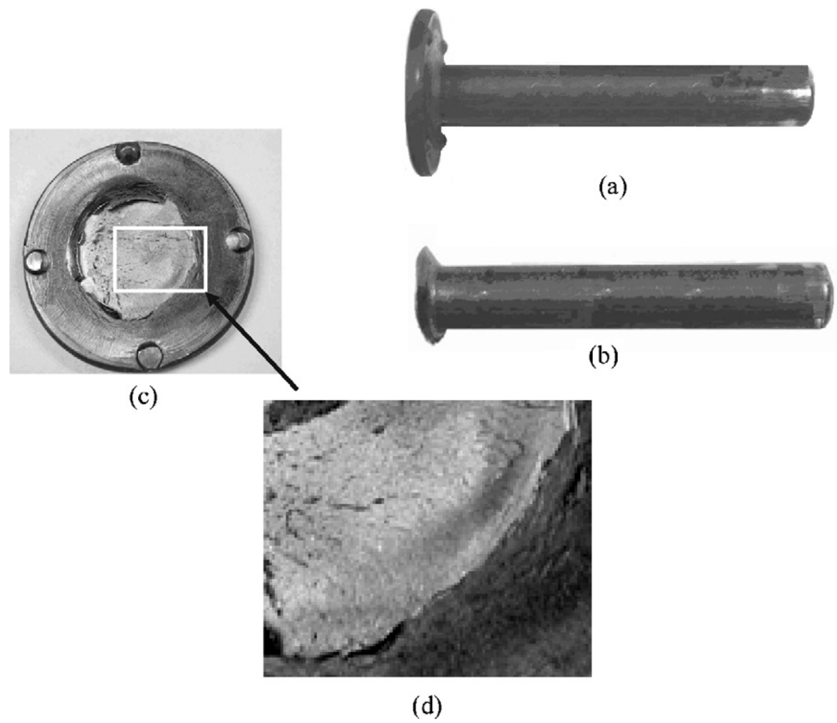

Fig. 1. Cold-headed industrial bolt: (a) without defect, using material 1, (b) shank of the defective bolt (material 2), (c) separated industrial bolt head due to an internal crack (material 2), and (d) magnified detail of the ductile crack of the separated industrial bolt head (material 2).

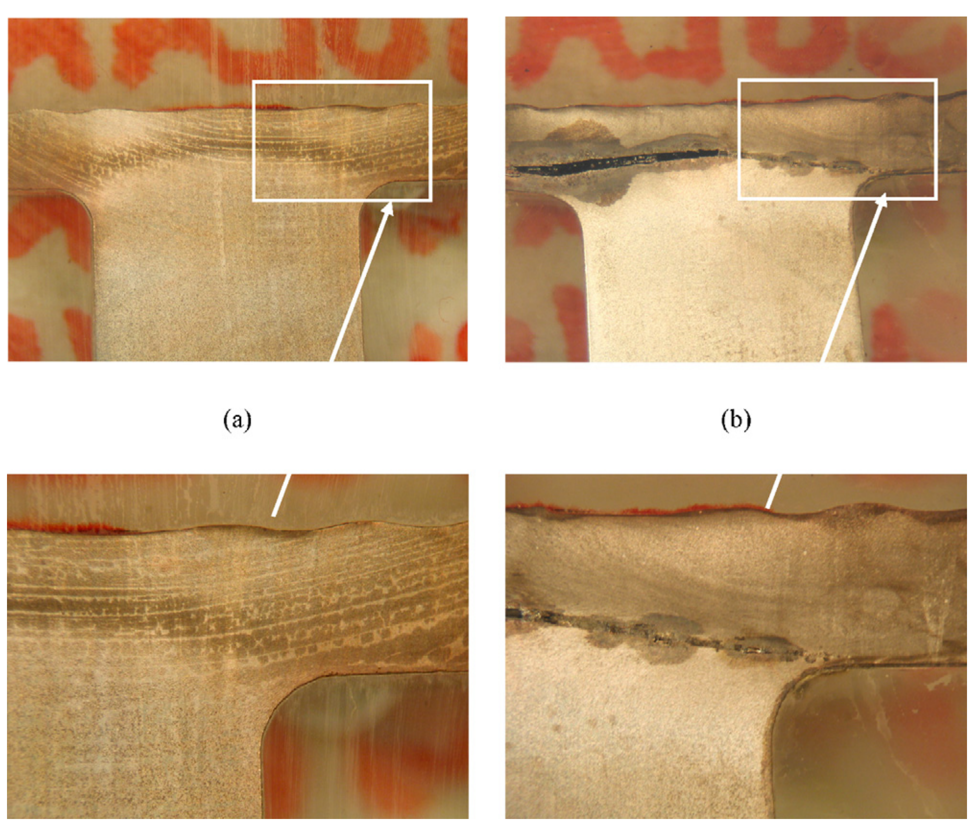

Fig. 2. Sectioned bolts revealing material flow inside the bolt head after etching with Fry's reagent (cupric chloride 36 g; 145 ml hydrochloric acid; 80 ml water): (a) without defect bolt (material 1), (b) with defect bolt (material 2).