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Macroscopic strength and failure properties of flow-drill screw connections

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ABSTRACT

Force–displacement responses and failure behaviour of connections using flow-drill screws to join aluminium sheets were investigated under various quasi-static loading conditions. This included single connector tests under tensile, shear and combined tensile and shear loadings, using cross test coupons in a new test set-up, and peeling and single lap-joint tests. The strength of the connection increased with the amount of shear loading, while the ductility decreased. No effect of the anisotropy of the sheets on the behaviour in the single connector tests was found. Axial crushing tests of aluminium single-hat sections joined with flow-drill screws were also performed. Two connection failure modes not observed during the single connector test were found in these tests. For comparison, equivalent single connector and component tests were carried out for self-piercing rivet connections. Similar trends with respect to the ductility, maximum force and shape of force–displacement curves were observed for the two connections, but the local failure modes were different.

1. Introduction

Joining with flow-drill screws (FDS) is a technology which may be used to join a variety of dissimilar materials, and is increasingly used to join aluminium parts in the load bearing structure of cars. By this technique sheets, extrusions, castings or combinations of these may be joined with a high strength steel screw. The joining process is a one-step procedure consisting of six stages, as shown in Fig. 1 (a) warming up due to friction between the screw and the sheet, (b) penetration of the sheet material, (c) forming of the draught, (d) thread forming, (e) full thread engagement and (f) tightening (EJOT). A pilot hole is usually drilled in the top sheet prior to joining. One of the main advantages with this technology is that tool access only is required from one side of the assembly. This may enable the process to be used in configurations where other joining techniques fail.

The FDS process is based on the technology of flow drilling (also called form drilling, thermal drilling or friction drilling), which is a method for making holes in metals; see e.g. Head et al. (1984). A synthesis of several studies on the flow-drilling process was given by Miller and Shih (2006), including measurement of thrust force and torque, study of microstructural alterations, flow drilling of cast metals, tool wear and analytical and finite element modelling. A literature survey revealed no publications concerning the FDS process.

No publications have been found on connecting two aluminium sheets with flow-drill screws. However, an experimental study of FDS connections was published by Szlosarek et al. (2013), who investigated the behaviour of a carbon-fibre-reinforced polymer plate joined to an aluminium plate. They performed tests by loading the connection in shear, tension and different combinations of shear and tension, and found that the failure load was similar for all load combinations, but observed two different failure modes.

Even though little information about FDS connections is found in the open literature, other related joining technologies used in the automotive industry, e.g. resistance spot welding and self-piercing riveting, have been widely covered and can be used as guidelines for experimental studies of FDS connections. Examples of experimental strategies for characterization of connections are presented in the following.

The common approach to study the behaviour of connections is to subject test coupons, consisting of a single connector joining two metal plates, to different controlled macroscopic load paths.

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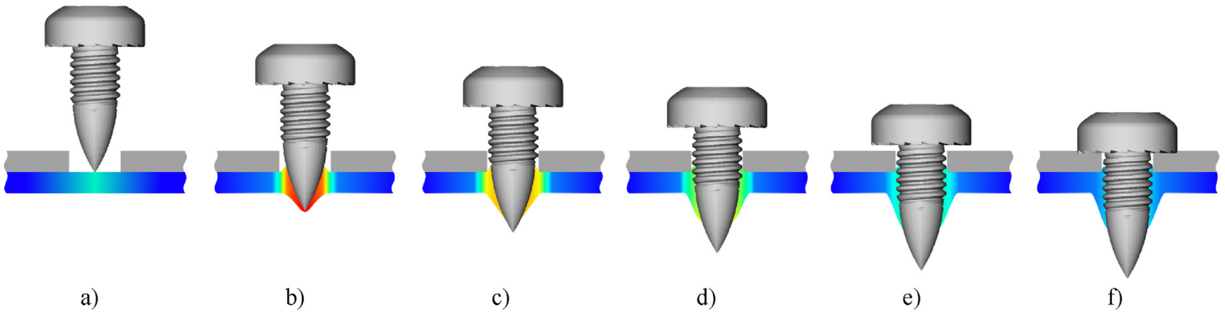


Fig. 1. Different stages of the flow-drill screw process. (a) warming up. (b) penetration of the material. (c) forming of the draught. (d) thread forming. (e) full thread engagement. (f) tightening.

Typical paths are tensile, shear, different combinations of tensile and shear and peeling loads.

Pedreschi and Sinha (1996) investigated the potential of press-joining in cold-formed steel structures by means of a series of lap-shear and bending tests. Lennon et al. (1999) did a comparative investigation of the mechanical behaviour of clinching, self-piercing rivet, pop rivet and self-tapping screw connections in thin gauge steel using the shear dominated lap-joint test. Similarly, Di Lorenzo and Landolfo (2004) carried out a comparative study of the shear response of blind rivets, circular press-joints and self-piercing rivets joining two and three steel sheets. The lap-joint specimen was used in the tests, with two connections in each sample. Briskham et al. (2006) performed lap-shear and peeling tests to assess the functional suitability of self-piercing rivet, resistance spot weld and spot friction joint connections for use in aluminium automotive structures.

Langrand et al. (2002) carried out experimental studies on the behaviour of blind rivets, which are commonly used in modern fighters and commercial aircraft frameworks. They did quasi-static and dynamic single connector tests on aluminium tension and lap-joint specimens instrumented with strain gauges.

The spot welded connection is probably the most investigated connection type used in the automotive industry. Lee et al. (1998) utilized a special designed test fixture similar to the Arcan type set-up (Arcan et al., 1987) to investigate the quasi-static behaviour of spot welded steel coupons under tensile, shear and various combined loadings. Wung (2001) carried out lap-shear, in-plane rotation, peeling, normal separation as well as different combined loading mode tests. In addition, a more sophisticated test with a more complex combined load path was performed (Wung et al., 2001). Langrand and Combescure (2004) used an Arcan type test to characterize the spot weld behaviour under tensile, shear and combined loading modes, and performed tensile pull-out, single lap-shear and peeling tests. This work was extended by Langrand and Markiewicz (2010) to include dynamic testing.

Self-piercing riveting (SPR) is a joining technology similar to FDS. The shear, tensile and combined shear and tensile quasi-static load responses of SPR connections between aluminium extrusions were investigated by Porcaro et al. (2006a). They also studied the influence of the plate thickness, rivet geometry, material properties and loading conditions (Porcaro et al., 2006b), and conducted dynamic tests to assess the rate effect on the behaviour of SPR connections (Porcaro et al., 2008). Sun and Khaleel (2005) investigated the quasi-static behaviour of SPR connections using cross-shaped tension specimens. This work was extended to also include dynamic testing (Sun and Khaleel, 2007). Similar and dissimilar materials were joined, and tests were carried out using cross tension, lap-shear and peeling specimens.

As there is a lack of knowledge about the behaviour of FDS connections in the peer-review literature, thorough experimental studies are required on this topic to provide a better understanding of the connections in order to allow for reliable designs of future vehicle structures.

Based on previous work on mechanical fasteners an experimental programme was carried out to investigate the behaviour of single connector FDS connections under various quasi-static loading conditions. In addition, quasi-static and dynamic component tests were carried out in order to investigate the structural behaviour of the connections under complex, non-controlled load paths. To assess the behaviour of FDS connections compared to other mechanical fasteners, an equivalent experimental programme was carried out for SPR connections.

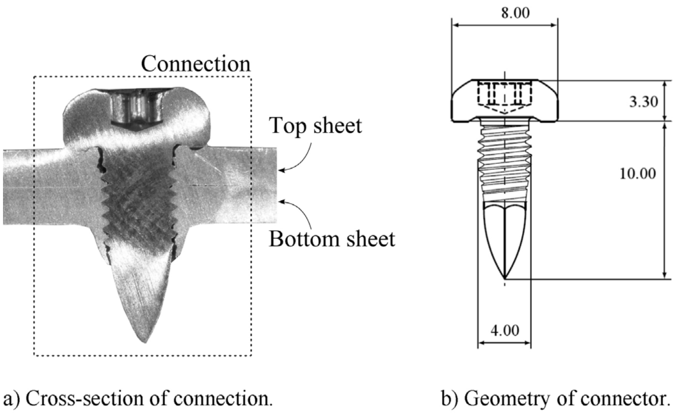
2. Connector and sheet material

In this work it is distinguished between the terms “connector” and “connection”. The term “connection” is here defined as *the system which mechanically fastens two or more parts together*. This definition is based on the definition of a connection in Eurocode 9 (CEN, 2007). The “connector” is in this work *the steel screw that is used to form the connection*. Thus, the connection is the system comprised of the connector and the surrounding aluminium sheet material (see Fig. 2 (a)).

The connector used herein was an M4 screw with a nominal length of 10 mm, made of case hardened mild steel, with standard tip and produced by EJOT. A cross-sectional view of the connection and the geometry of the connector are shown in Fig. 2(a) and (b), respectively.

The plates used in the single connector and component tests were rolled sheets of AA 6016 in temper T4 with a nominal thickness of 2 mm. Due to the rolling procedure such sheets usually exhibit orthotropic plastic anisotropy (Lademo et al., 2009).

In order to assess the strength and anisotropy of the sheet material, uniaxial tensile tests were carried out in seven different



a) Cross-section of connection.

b) Geometry of connector.

Fig. 2. Connection and connector.