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Analysis of the structure and resulting mechanical properties of aluminium extrusions containing a charge weld interface

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ABSTRACT

This work describes a detailed study of the effect of the presence of a charge weld transition zone on the failure mode and local effective mechanical properties of the extrudate. To this aim a dedicated die was designed for which the flow pattern was such that the effect of the charge weld zone could easily be isolated. The effect of the charge weld zone on the damage and failure evolution during testing of tensile samples loaded to various strain levels was demonstrated and analysed in detail. The evolutionary geometry of the bond plane was visualised by serial sectioning of the extrudate followed by metallographic characterisation. An even better insight was obtained by in-situ observations during tensile testing of samples containing a weld seam. It is shown that the mechanical performance is largely controlled by the density of the oxide particle population at the charge weld boundary. Crack initiation is determined primarily by the central weld seam interface segment containing a more or less fractured layer of oxides. The peripheral sides of the weld seam region failed in a ductile manner characteristic of regular base material. The main conclusion of the work is that the flow pattern in the die determines the length and shape of the charge weld interface as well as the drop in mechanical properties due to fracturing of the oxide layer.

1. Introduction

In aluminium extrusion the forming process takes place from a number of sequentially loaded billets, with each billet representing one extrusion cycle. As the billets are pre-heated to bring them up to the extrusion temperature, unavoidably there is a relatively thick layer of oxides on the outside of the billet. In early work of Beck et al. (1967) it was shown that the oxide layer increases in thickness through growth of both amorphous and crystalline Al_2O_3 phases at temperatures between 450 °C and 575 °C. As shown by Van Rijkom and Bolt (2000) the oxide layer can grow to a thickness in the order of several hundreds of nanometres, especially in the case of alloyed aluminium heated in a gas furnace. This layer of oxides, in particular the oxides on the planar surfaces of the billets brought in contact, will flow through the die and end up in the extrudate. Hence the initial contact between the billets consists of two heavily oxidised planar surfaces which are deformed during extrusion, leading to a transition boundary with a shape defined by the material flow in the die: a so-called charge weld interface (Valberg, 2002). During metal flow through the die the brittle oxide layer fractures and fresh solid aluminium flows locally through the gaps in the fractured oxide layer. The integrity of the final interface relies on this joining of virgin aluminium pressed through the gaps in the fractured oxide layer (Mohamed and Washburn, 1975). As a result of the varying process conditions and the evolving shape of the charge weld interface, the properties of charge welds of a given extrusion geometry will depend both on the position in the extrudate cross section and on the longitudinal location in the extruded length (Akeret, 1972). The effect of the transient process conditions was investigated by Nanninga et al. (2011), who studied the fatigue performance of the charge weld in transverse and longitudinal orientation and at different positions. In experiments with segmented billets composed of aluminium alloys types with a different etching response, Valberg (2002) obtained flow patterns showing the relative velocities in the die. At certain areas in the die the material remained nearly motionless, causing so called dead metal zones. Adjacent to these areas and at aluminium-die contact zones where metal flow is retarded too, shear strains are high and extensive oxide layer break-up takes place. Further away from these locations, typically in the middle of an extrusion web, fracturing of the oxide layer

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becomes less effective and the solid oxide layer is more or less preserved. Similarly, the occurrence of more or less intact oxide layers was also observed following the transformation of particulate machining chips into extruded shapes (Tekkaya et al., 2009). In a further elaboration by Güley et al. (2013) it was shown that bonding was strongly dependent on the local deformation conditions related to the position inside the die. In recent work by Cooper and Allwood (2014) the solid bonding of oxidised metallic interfaces is considered, thereby taking into account the additional effect of oxidation of the newly formed aluminium surface by oxygen trapped in the gaps of the roughness asperities. The influence of the tooling design on flow related charge weld formation was investigated by Den Bakker et al. (2013) in extrusion experiments utilising different tooling designs yielding the same profile geometry but with different flow profiles within the die. Whilst the total transition length was found to be relatively independent of the tooling geometry, the individual metal streams flowing through the ports in the die were found to be closely controlled by the port shape and the port layout. Their results are in line with findings from Mahmoodkhani et al. (2014), who showed in simulation studies of metal flow that modifications to the feeder dimensions of a flat die influences the onset and extent of the charge weld transition.

The present paper focuses on the evolutionary mechanical properties of the extrusion charge weld, analysed in the light of the solid bonding process of a planar, pre-oxidised brittle surface layer on a ductile metallic substrate deformed into complex 3D-contour formed during material flow through the die. The outcome of this research serves to improve extrusion process efficiency by reducing unnecessary scrap allowances in the elimination of the approximated charge weld zone through enhanced insight into the charge weld performance in relation to the transition length.

2. Experimental

2.1. Materials

In this study samples were produced through lab scale extrusion trials with an AA6082 aluminium alloy. This is a medium strength alloy, hardenable through the formation of various Mg–Si rich precipitates. The composition of the alloy used is reported in Table 1.

Through the addition of the dispersoid forming elements Mn and Cr recrystallisation following hot extrusion is suppressed and a fibrous microstructure consisting of heavily deformed grains containing a recovered sub-grain substructure is formed. The extrusion precursor was prepared by means of a vertical direct chill casting process, producing cylindrical logs of 168 mm diameter and 2 m in length. Casting was followed by a homogenisation heat treatment at 540 °C for 5 h and the billet was subsequently cooled by forced air cooling with an average cooling rate of over 200 °C/h. The grain structure of this material consisted of equiaxed grains with an average grain diameter of approximately 150 μm. The heat treated logs were reduced in diameter to 143 mm by milling, thereby eliminating the edge zone inherent to the casting process. After removal of the head and foot of the logs, billets of 300 mm were cut from the remainder of the cast logs for the charge weld experiments.

2.2. Extrusion shape and processing

The extruded shape consisted of a single hollow box-section type with a width of 90 mm and a height of 35 mm (Fig. 1), leading to a circumscribing circle diameter of 97 mm. The wall thickness of the thinned sections of the longitudinal webs was approximately 5.5 mm. The nominal extrudate cross sectional area was 1340 mm^2. Given the dimensions of the billet the effective overall extrusion ratio was 13. This shape was designed with the objective to establish a semi-industrial scale extrusion geometry fitting within the confines of the available die layout discussed hereafter. Other shapes such as a circular and square tubular forms were considered, however these options were rejected due to limitations in maximum extrudate size and available sample geometries intended for mechanical testing with the intent of obtaining quantitative results. The chosen shape enables samples to be fabricated with features representative for the intended investigation documented in this publication and associated studies focussing on longitudinal weld seams and microstructure evolution.

A 2-part porthole die having three ports (Fig. 1c–f) was designed especially for the purpose of this research. At the inlet side of the die, the billet is split into three streams and the material flows through the ports into the weld chamber where the metal streams are rejoined to form the continuous profile cross section. Two identically shaped ports each feed the short side webs and the adjoining parts of the long lower web (webs designated 1-A and 1-B in Fig. 1b). Material flowing through the single large port forms the top web of the extrusion, bounded at the corners by the weld seams (web designated 2 in Fig. 1b). Hence material from each web can be individually traced back to the related port in the die. The geometry of the extrudate enables characterisation of the flow phenomena dictated by the extrusion tooling and the assessment of the mechanical properties of the opposing longitudinal webs in transverse direction, as presented in Fig. 2.

By sectioning the extrusion to a pre-defined thickness and eliminating the short transverse webs, paired tensile samples are obtained of which one sample containing a weld seam (denoted tensile sample type 'W') originates from the combined flow of material from the two small ports feeding webs 1-A and 1-B defined in Fig. 1b and an equivalent sample not-containing a central weld seam (denoted tensile sample type 'T'), from the opposite side of the extrusion fed from the large port. Hence two tensile samples each with a total length of 90 mm and a parallel length of approximately 50 mm can be manufactured from one cross-sectional segment. For these experiments the thickness of the samples was fixed at 5 mm.

Prior to extrusion the billets were pre-heated in an air circulation batch furnace to a pre-set temperature of 540 °C, allowing ample time for the material to achieve a stable temperature. Extrusion processing consisted of loading a pre-heated billet into a 10 MN hydraulic extrusion press operating in the direct extrusion mode, upsetting the billet to ensure complete filling of the container and subsequently extruding the billet through the die, resulting in a length of the desired extrudate geometry. Following completion of the extrusion cycle a subsequent billet is loaded and the process is repeated under constant settings. In this manner a continuous extruded length is produced from multiple billets. The billet change-over can be traced on the extruded length through a "stop mark". This is a circumferential mark on the extrudate surface formed when the extrusion is interrupted to load a new billet and the stationary aluminium adheres to the die bearing. As extrusion recommences the aluminium-die interface detaches, leaving a mark on the extrudate. This stop mark serves as the initial reference point for the charge weld transition length.

In the experiments the ram speed was fixed at a value of 5 mm s^{-1}, resulting in a product speed of approximately 60 mm s^{-1}. Directly at the press exit the emerging extrudate was rapidly cooled by means of a water quench tunnel with a length of 1000 mm. In preparatory tests it was established that the average extrudate quench rate between the press exit and room temperature exceeded 30 °C s^{-1}. The set of process conditions imposed should be more than adequate to achieve complete solutionising and hence a maximum strength and toughness after artificial aging.