



Exploring a Novel Process for Reducing Aluminum Extrusion Process Scrap

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Abstract. Extruded aluminum supply chains are materially inefficient with around 40% of the billet likely to be scrapped before the profile is embedded in a product. One of the largest sources of scrap is the removal due to weld integrity concerns of the tongue-shaped transverse weld(s) that forms between consecutively extruded billets. Process setting and die geometry optimization can decrease the weld length (and hence scrapped material) by modest amounts. We explore a process for significant scrap savings using profiled dummy blocks to generate shorter welds by compensating for the differential metal flow velocities across the billet cross-section as it flows through the die ports. We develop a design process for defining the profiled dummy block shape. For a given part and press, we first define an ideal dummy block shape by extracting the velocity field from finite element simulations of the conventional process and assuming perfectly rigid tooling. Next, we rationalize the tool shape using stress and deflection limits (preventing plastic deformation and interference with the container wall) and ductile damage limits for the billet to prevent cracking. We then simulate the likely effect of the rationalized dummy block design on back-end defect removal. The methodology is demonstrated for four profiles of increasing complexity. The process' potential is evaluated experimentally using billets machined to match the ideal dummy block shape. The results show that profiled billets can achieve weld length reductions >50% for simple shapes. We demonstrate that multi-profile tooling can deliver scrap savings across a family of similar profiles.

Keywords: Material Efficiency · Transverse (charge) welds · Dummy block

1 Introduction

The transverse weld can be the most significant source of extrusion scrap, representing an average loss of 20% [1]. The weld is formed because the initially planar billet-billet interface elongates as the material passes through the die (Fig. 1a). The elongated interface is removed for many load-bearing applications due to its weak mechanical properties [2–4]. Finite element models (FEMs) have been used to predict the reduction of the transverse weld length from process parameter (e.g., temperature, ram speed, friction conditions) and die geometry optimization. Oberhausen et al. [5] report that these optimizations do not achieve a weld length reduction greater than 15%. Oberhausen et al.

demonstrate that additional savings might be achieved by changing the geometry of the initial billet-billet interface in the container (Fig. 1b); however, they only demonstrate it for a round bar profile using plasticine clay billets. The goal of this current study is to further evaluate the profiled dummy block concept.

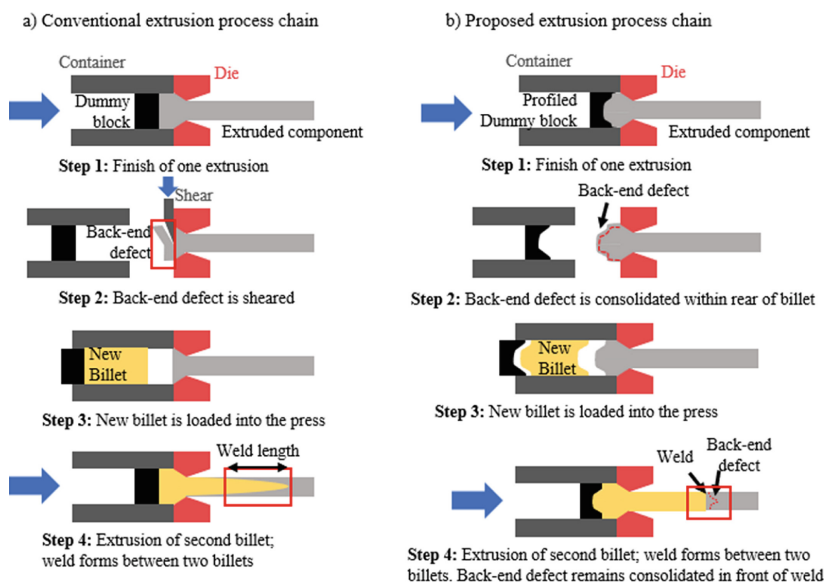


Fig. 1. The (a) conventional and (b) proposed extrusion process steps.

1.1 The Profiled Dummy Block and Billet Concept

The profiled dummy block and billet are designed to generate shorter welds by using a concave dummy block and billet-billet interface to compensate for the differential metal flow velocities across the billet cross-section as it flows through the die. The result is a near-flat transverse weld, requiring a minimal length of profile to be scrapped. For more complex profiles, asymmetric dummy block concavities will be required, or multiple concavities (one for each die port) for the case of hollow profiles extruded using porthole dies. A profiled dummy block designed for a specific profile and press would maximize scrap savings; however, the requirement to change the dummy block as well as die when extruding a new profile may add a significant burden to the extruder; therefore, we can also consider multi-profile dummy blocks that deliver scrap savings over a family of similarly shaped extrusion dies (and extruded profiles).

The profiled billets may be created by casting, ex-situ forging of conventional billets before being loading into the press container, or in-situ upsetting/forging within the press container as part of the initial extrusion stroke with additional gas escape vents in the dummy block/forging block concavities to prevent air entrapment. The profiled dummy block concept requires the absence of the butt shear to preserve the profiled

billet-billet interface. Figure 1b depicts one method of then dealing with the back-end defect: extrusion of the defect to a consolidated quantity of scrap in front of the transverse weld, which then requires scrapping of that section of profile. Alternatively, back-end defect removal can rely on using peeled billets or Dick's method [6], leaving a "skull" in the container.

1.2 Scope of This Article

The goal is to develop a profiled dummy/forging block and billet design methodology. As a first step towards evaluating the design methodology, we then extrude billets that have been machined to the ideal profiled geometry.

2 Design Process for Profiled Dummy Blocks

Fig. 2 shows the proposed design process. First, the geometries of idealized (rigid) dummy blocks and profiled billets are determined using FEMs. Next, these idealized designs are rationalized, beginning with a geometric rationalization ensuring that the profiled dummy blocks and billets can mate during the extrusion stroke and then decouple during ram extraction. The dummy block geometry is then further adjusted to ensure no plastic and minimal elastic deformation of the profiled dummy block based on a revised FEM that models the dummy block as a deformable body. Finally, a FEM of the ex-situ billet hot forging process ensures that the ductile damage endured by the billet will not cause billet cracking.

2.1 Step 1: Deriving Idealized (Rigid) Profiled Dummy Block Geometries

A FEM of the conventional extrusion process generates the steady-state velocity field for points throughout the workpiece. Using MATLAB, a point (P) can then be iteratively tracked using Eq. (1), where $v_{P,old}$ is the velocity vector attributed to the initial position and Δt is the modeled time increment. For every increment, $v_{P,old}$ is calculated using linear interpolation from the velocity vectors defined for the four neighboring nodes in the relevant tetrahedral element.

$$P_{new} = P_{old} + v_{P,old} \Delta t \quad (1)$$

$$P_{old} = P_{new} - v_{P,new} \Delta t \quad (2)$$

This strategy is applied to a plane of points corresponding to the conventional flat billet-billet interface (Fig. 2b, Step 1.1). The plane is tracked for time T to define the conventional weld geometry at the exit of the die (Fig. 2b, Step 1.2). A new plane of points is then defined corresponding to the flattened end of a shortened weld (Fig. 2b, Step 1.3). This new plane is tracked for time T backward through the velocity field (Eq. (2)) to define the new shape of the billet-billet interface that results in the defined shortened weld (Fig. 2b, Step 1.4).

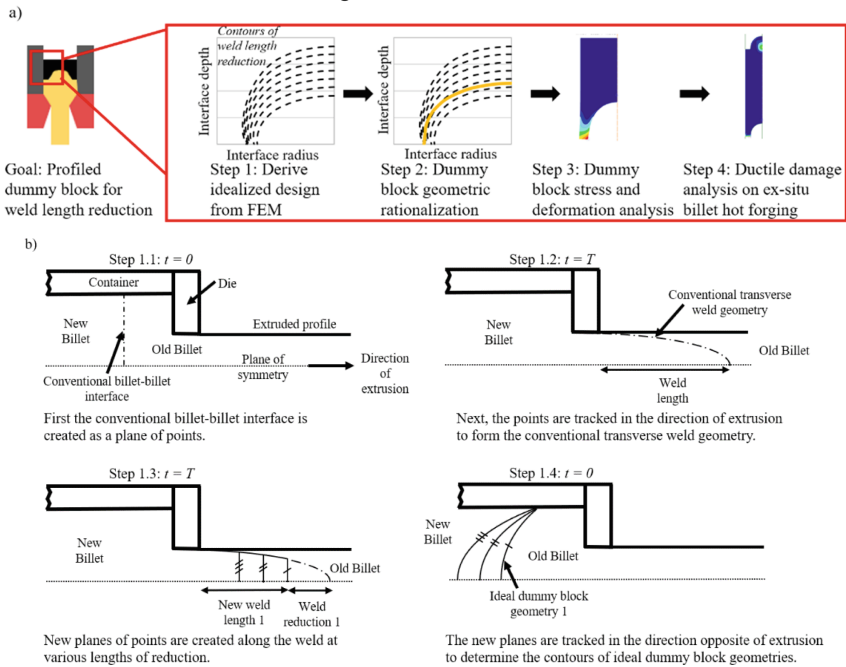


Fig. 2. (a) Profiled dummy block and billet design process. (b) The velocity field method for generating the idealized profiled dummy block and billet geometry (Step 1).

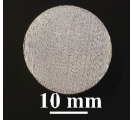
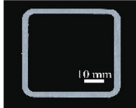
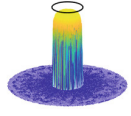
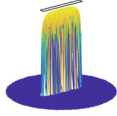
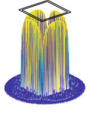
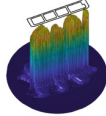
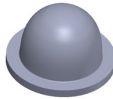
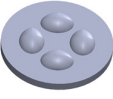
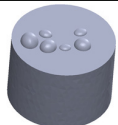
2.2 Steps 2–4: Rationalizing the Dummy Block Design

The shape is first adjusted to ensure geometric compatibility for mating and decoupling between the dummy block and billet, and then further adjusted to ensure that the dummy block does not experience plastic deformation or excessive elastic deformation (< 1 mm radial expansion) that would cause interference with the container wall under the pressure of the extrusion process. The stresses and subsequent deformation on the dummy block can be reduced by adjusting to lower reduction designs (thickening the outer dummy block wall). Finally, to prevent billet cracking, the ductile damage imparted on the billet during ex-situ hot forging must be less than the critical value to cause a crack to form. Christiansen et al. [7] find that the *Cockcroft-Latham* [8], *Ayada* [9], and *Shear* [10] models of ductile damage can predict the onset of cracking in cold aluminum samples with their relative accuracy determined by the predominant stress state in the metal. We also use these ductile damage models to evaluate the onset of cracking during ex-situ hot forging of conventional billets into profiled billets (cylinders with profiled end faces).

3 Testing the Design Method

We follow the methodology outlined in Sect. 2 to design profiled dummy blocks and billets for axisymmetric rod, rectangular bar, hollow square tube, and complex multi-hollow profiles (Table 1). We then experimentally test the first two steps of the design methodology (see Fig. 2a) by extruding profiled billets for these shapes.

Table 1. Profiles studied. Note that different presses and billet diameters were used.

Profile	AA6061 Round bar	AA6061 Rect. bar	AA6061 Sq. hollow	AA6082 Multi-hollow
Profile image	 Base case: Ø23.08 Small: Ø 16.2 Large: Ø27.94			
Die image & # of die ports	Die entrance  Die exit & 1	Die entrance  Die exit & 1	Die entrance  Die exit & 4	Die entrance  Die exit & 7
Weld geometry (FEM) & conv. weld length (mm) [FEM vs Experimental]	 & [525 vs 500] (base case)	 & [5000 vs 5250]	 & [950 vs 1000]	 & [975 vs 1000]
Profiled billet design (3D model)	 Round bar profile-specific design 2			
Profiled billet design (experiment)	 Round bar profile-specific design 2			Not tested experimentally due to unavailability of the press

3.1 Step 1: The Geometry of an Idealized (Rigid) Profiled Dummy Block

For each profile studied (see Table 1), a FEM of the conventional extrusion process was produced using Altair Inspire Extrude Metals [11]. The accuracy of the FEMs were validated by checking that the simulated ram forces and weld geometries were within $\pm 10\%$ of the experimentally measured ram forces and weld geometries. Following Sec. 2.1, design contour maps were created that relate the geometry of the profiled dummy blocks and billets to the expected weld length reduction (Fig. 3).

3.2 Steps 2–4: Geometric Feasibility, Deformation, and Ductile Damage Analysis

Geometric Feasibility. The colored lines on Figs. 3a, c, d show the rationalized dummy block and billet profile cross-sections.

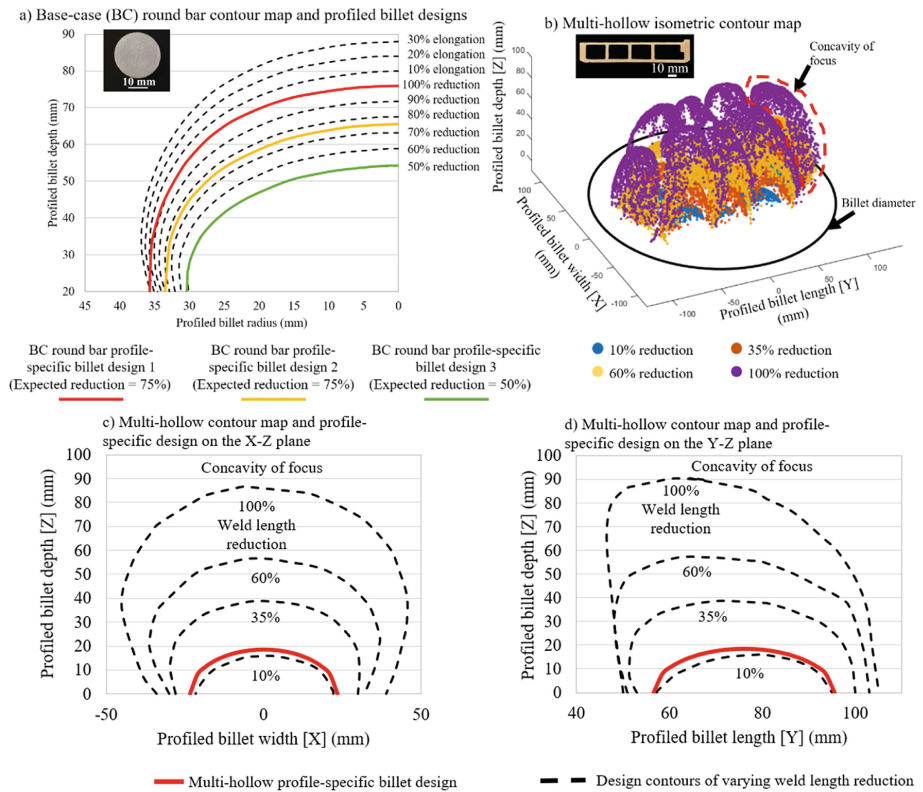


Fig. 3. Examples of the profiled dummy block/billet design contour maps with plotted profile-specific billet designs. The dotted lines depict the shape of the dummy block/billet concavities. The percentages refer to corresponding weld length reductions. Such contour maps were also produced for the rectangular bar and square hollow profiles but are excluded here for the sake of concision.

For the base-case round bar (Fig. 3a), a curve following the contour of 100% weld length reduction is chosen as profile-specific billet design 1. The curve is adapted with a fillet that spans the 25% elongation line, to open the entrance to the concavity. Profile-specific billet design 1 (red line in Fig. 3a) is, therefore, expected to result in a 75% reduction of the weld length: 100% reduction away from the die but a 25% elongation towards the die. Profile-specific billet design 2 (yellow line in Fig. 3a) is also created which begins on the 75% reduction contour and has a fillet which ends at the 90% reduction contour. Profile-specific billet design 2 is therefore expected to result in a 75% reduction. These geometrically feasible designs were chosen for the experimental trials.

At this stage of development, the experiments were conducted using machined two-piece profiled billets, acting as proxies for profiled dummy and forging blocks.

Dummy Block Deformation. De-coupled FEM analyses using DEFORM® [12] were used to assess the stresses and strains present on the dummy blocks for the base-case round bar and multi-hollow profiles under extrusion loads. A de-coupled analysis was chosen in place of a single, coupled simulation with both deformable billets and tools in order to decrease the simulation time. The de-coupled model is first run with the dummy block, container and die as rigid solids, and the extrusion billet as a plastically deformable object. The simulation is run to die-break through, and then the step with the peak ram forces is extracted. In the next phase of the simulation, the dummy block was modeled as an elasto-plastic solid with the material properties of TQ1 tool steel at 450 °C (yield strength of 1200 MPa). The forces experienced by the back of the billet during the first phase of the simulation are interpolated onto the dummy block's face during the second phase. The container was modeled as a rigid body. The container and die contact were modeled using sticking friction, and the dummy block-billet contact was assumed to be frictionless as lubricant is typically used at this interface [13, 14]. The regions within the die, experiencing significant deformation, have a fine mesh (tetrahedral elements with a length roughly equal to 1% of the billet radius) and the areas undergoing minimal deformation, such as the middle of the billet (by length) in the container, have a coarse mesh (3–10% of the billet radius). This meshing strategy maintains accuracy, while reducing the total number of necessary elements and therefore also simulation time. Figure 4 shows the plastic strains expected on the round bar and multi-hollow profile dummy block designs. The plastic strain expected on the base-case round bar profile-specific dummy block design 2 is non-zero (Fig. 4a); 3.8% radial plastic strain is expected on the thin dummy block edge, exhibiting about 1.6 mm radial displacement.

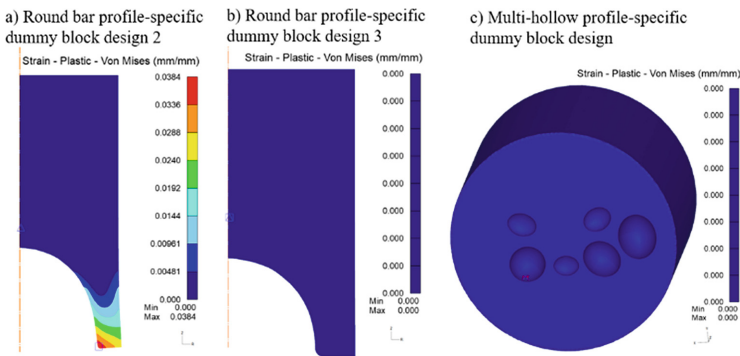


Fig. 4. The simulated plastic strain expected on the (a) base-case round bar profile-specific dummy block design 2 and (b) base-case round bar profile-specific dummy block design 3, as well as the (c) the multi-hollow profile-specific dummy block design. Note that the centerline in the images (a) and (b) denotes an axisymmetric simulation.

We therefore iterate on the round bar profiled dummy block design, lowering the reduction to 50% of the conventional weld length, adapted to be geometrically feasible

(the green line on Fig. 3a). After this iteration the base-case round bar profile-specific dummy block design 3 experiences zero plastic strain (Fig. 4b) and just 0.1 mm of elastic radial displacement. The multi-hollow design also achieves zero plastic deformation (Fig. 4c) with 0.2 mm of elastic radial deflection for the 10% weld length reduction design and is left unchanged.

Hot Forged Billet Ductile Damage Analysis. First, we quantify the damage suffered by the billets using FEMs of ex-situ hot forging (425 °C) of flat, full-length, AA6061 billets within a container (sticking friction assumed) using a top platen with the dummy block geometry and the negative (convex) shape on the bottom platen. Figure 5 shows the maximum simulated damage values for creating the base-case round bar profile-specific billet design 3. Both the Cockcroft-Latham and Ayada criteria predict maximum damage (0.22 and 0.55 respectively) on the corner of the bottom flat edge just before the billet forming is complete. The Shear criteria (maximum damage: 1.52) predicts the damage will concentrate on the outer diameter of the bottom length of the billet due to the frictional shear stresses between the container wall and the billet.

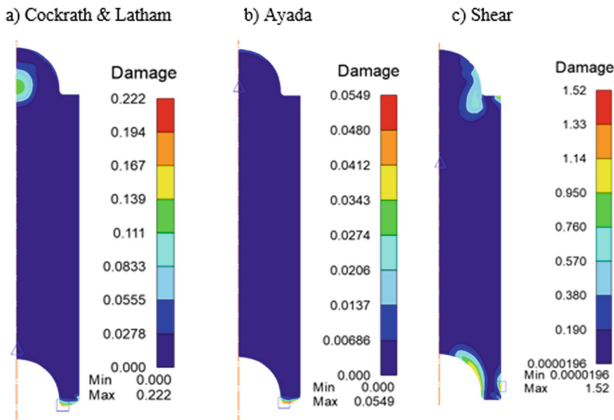


Fig. 5. Simulated maximum billet ductile damage during ex-situ AA6061 billet hot forging. Note that the centerline in the images denotes an axisymmetric simulation.

To evaluate whether this level of ductile damage is sufficient to cause billet cracking, we then conduct hot compression tests (500 °C) on cylindrical, taper, flange, and shear samples (Fig. 6), per the experiments of Christiansen et al. [7]. Informed by FEM, these samples are each compressed to create ductile damage equivalent to the maximum ductile damage experienced during hot forging of the billets according to the various damage criteria: 57% compression on the cylinder, 41% on the taper, 35% on the flange, and 11% compression on the shear sample. Once cool, each compressed sample was then inspected for cracking. No cracks were found on the samples after compression to these values, indicating that hot forging of conventional flat-end cylindrical billets into profiled billets would not cause billet cracking.

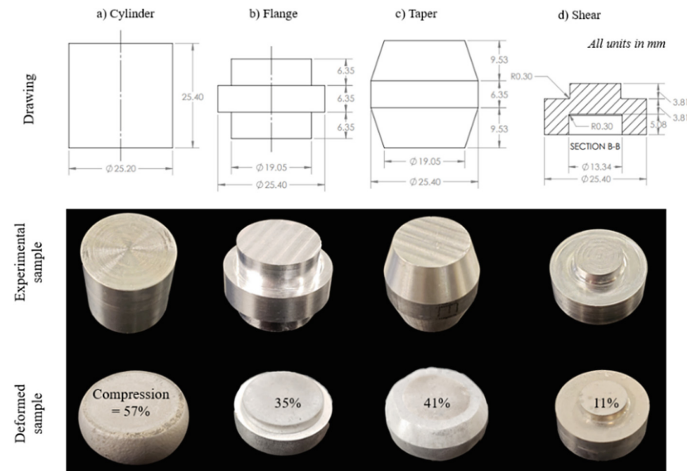


Fig. 6. Experimental samples tested in the ductile damage derivation procedure.

4 Experimental Results and Discussion

Figure 7 shows the weld length reduction results of the profiled billet extrusion trials. Figure 8 shows the weld geometries achieved. Figures 7 and 8 show that weld length reductions were achieved across the different profiles (ranging from 10% to 75% reductions) but weld length reductions were much smaller for the hollow profiles (around 10%) compared to the solid profiles. This is largely because for the hollow profiles the edges of neighboring dummy block/billet concavities that correspond to large weld length reductions (larger concavities) are very close and small deviations from the perfect geometry can result in a significant extension of the weld towards the die (see Fig. 3b).

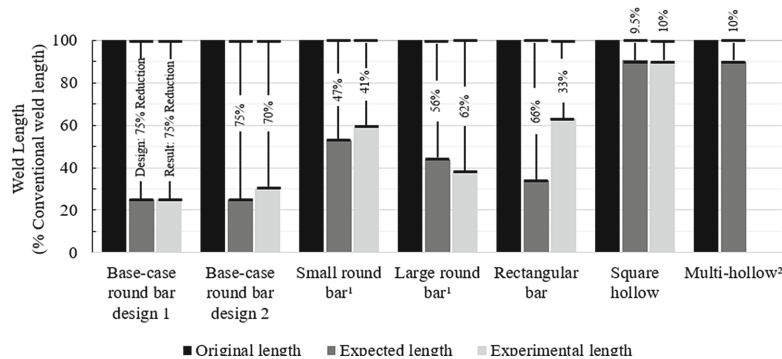


Fig. 7. Expected and achieved weld length reductions using profiled billets. The base-case profile-specific billet designs 1 and 2 were different designs both intended to achieve a 75% weld length reduction in the base case (mid-sized) round bar. 1: The design 2 was also used during extrusion of the smaller and larger diameter round bars. 2: The multi-hollow profile was not evaluated experimentally due to unavailability of the press and die.

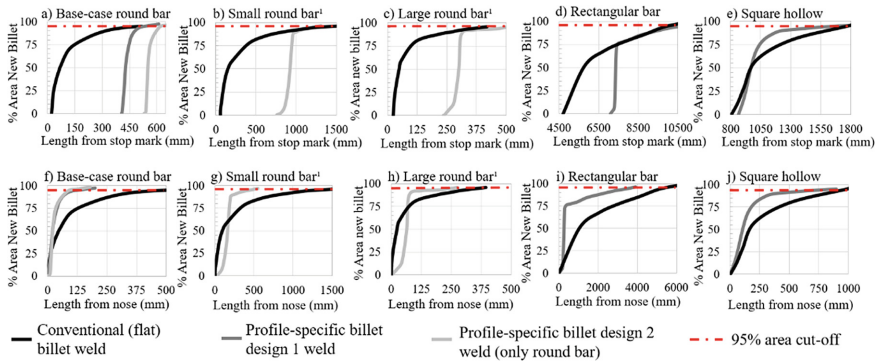


Fig. 8. Experimental conventional and profiled billet transverse weld geometries. 1: The design 2 was also used during extrusion of the smaller and larger diameter round bars.

For the round bar and square hollow profiles, the expected and achieved weld length reductions were relatively close; however, the discrepancy on the rectangular bar was significant (a 66% designed for weld length reduction vs. only 33% achieved experimentally). Examination of the rectangular bar transverse weld created using the profiled billets revealed that the discrepancy between theory and experiment was due to interpolation of the profiled billet designs between the major and minor axis of the ellipsoid shaped concavity. The profiled billet geometries for the rectangular bar were designed by using the velocity field method to create the profile-specific billet contours along the major and minor axis of symmetry. These boundary curves were then lofted (interpolated), along a third boundary curve along the billet-billet interface, using SolidWorks [15] to create a full 3D-design. Along the major and minor axes of the profile, the weld length reductions achieved were 63% (close to the 66% intended). Therefore, it was in the space between the major and minor axis of the rectangular profile that the weld length reduction was significantly comprised. The lesson is that the velocity field method should be used to design across the profiled dummy block and billet surface and not just along key axes and then relying on interpolation.

4.1 Effect on the Back-End Defect

The back-end defect contains a conglomeration of oxides and other contaminants from the billet skin [1, 16]. The billet skin ranges from roughly 0.05 mm to 0.5 mm in thickness [17, 18] depending on the billet quality. Point tracking in the extrusion FEMs (introduced in Sect. 3.1) is used to determine the potential effect on scrap generation from extruding the back-end defect through the die in order to preserve the profiled billet-billet interface. We focus on the case of the profiled dummy block and billet design for a 50% reduction in weld length for the base-case round bar profile (design 3 in Fig. 3a). The FEMs first simulated hot forging of a flat-faced billet and then extrusion of these profiled billets using the profiled dummy block. The length of the billet skin in front of the nose of the transverse weld (shown in Fig. 9) is used to calculate the volume of material necessary to be removed as part of the back-end defect. Conventional butt shearing would remove the last 10% of the billet length (in this case 20 mm, equivalent to 124,000 mm³ of

scrap). If instead, the conventional butt was extruded through with the next billet, then the back-end defect would be located in front of the transverse weld: an average billet skin thickness (0.25 mm) would contaminate roughly 350 mm of profile in front of the nose of the transverse weld, equivalent to $125,500 \text{ mm}^3$, roughly equal to the volume of the billet butt. For the case of the profiled billet (design 3 for the base-case round bar profile), the FEM results shown in Fig. 9 show that a 0.05 mm thick billet skin would contribute to a volume of $17,220 \text{ mm}^3$ of profile scrap (41 mm removed in front of the weld nose), and a skin thickness of 0.5 mm would contribute a volume of $98,250 \text{ mm}^3$ of profile scrap (235 mm removed) for a reduction of back-end defect scrap of between 20–85%. These savings are due to the concave dummy block shape concentrating the back-end defect into a smaller volume at the rear of the billet.

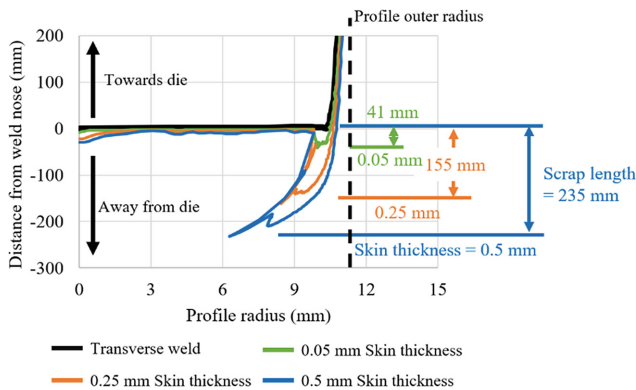


Fig. 9. The simulated geometry of the extruded back-end defect for the case of base-case round bar profile-specific design 3 given varying billet skin thicknesses.

4.2 The Potential for Multi-profile Tooling

Current industry practice is to replace the dummy block approximately weekly for maintenance [19, 20]; however, profiled dummy blocks may need to be changed with every change of die (and therefore profile extruded) unless profiled tooling can be designed that delivers savings across a family of similar tool designs (and extruded profiles). Figure 7 shows the potential for multi-profile dummy block tooling for the case of the simplest solid shapes (round rods). Figure 7 shows that a profile-specific billet design for achieving a 75% weld length reduction for a mid-sized round bar (extrusion ratio (ER) = 15) also achieves a 42% and 62% reduction in the weld length for larger (ER = 10) and smaller (ER = 30) bars respectively.

5 Conclusions and Future Work

This work has presented a methodology for designing profiled dummy blocks and billets that can be used to reduce the transverse weld length and subsequently the scrap created during direct extrusion. The experimental trials present promising results that the technique can be applied across a range of profile shapes. The profiled dummy block and billet concept appears most beneficial for solid profiles where larger weld length reductions can be achieved and where a family of similarly shaped profiles might use the same profiled dummy block and billet design to achieve scrap savings. Simulations suggest that this new concept could also reduce the scrap removed to eliminate the back-end defect. Future work will include: (1) an extrusion trial using a profiled dummy block to forge and then extrude profiled billets for the solid profiles analyzed in this work, (2) a theoretical and experimental study on the potential use of multi-profile tooling for solid profiles beyond the simplest case of round rods to include other common shapes such rectangular bars, hex-shaped, L-shapes, and star-shaped stock, and (3) analysis of the effect on the back-end defect in non-axisymmetric profiles, as well as experimental validation of back-end defect reduction.

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