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Perforation of welded aluminum components: Microstructure-based modeling and experimental validation

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ABSTRACT

Perforation of welded aluminum structures by small-arms bullets is studied both experimentally and numerically in this paper. From the chemical composition, artificial aging history, and welding procedure, the spatial distribution of the flow stress at ambient temperature of MIG-welded AA6082-T6 aluminum extrusions was determined by using a thermal finite element model and a nano-scale material model. The resulting flow-stress curves which are functions of the distance from the weld center line were used in a mechanical 3D finite element model to investigate the effect of the heat affected zone (HAZ) on the ballistic properties of welded aluminum extrusions. For experimental validation, 10 mm, 20 mm and 30 mm thick extruded profiles were processed and welded to correspond to the numerical method. Hardness measurements and ballistic impact experiments were performed in the weld metal, HAZ, and base material. Uniaxial tension tests were conducted for the base material of the 10 mm and 30 mm profiles. These tests provided sufficient data for experimental validation of the numerical method. Temperature distribution, hardness values, equivalent stress-strain curves, and ballistic limit curves are reported from both the experiments and the numerical simulations. In general, the experimental results correspond well with the numerical predictions and the predicted ballistic limit velocities are within 10% of the experimental ones, suggesting that this method is a possible alternative to performing expensive and time consuming experimental testing in the early stages of the design of protective aluminum structures. The HAZ was found to impair the ballistic performance locally, but the difference between the ballistic limit for the base material and HAZ was never more than 10% in this study.

1. Introduction

Most studies concerning the ballistic capabilities of structures involve perpendicular impact on flat, flawless surfaces where the effects of connections are disregarded [1–5]. However, size and shape limitations inherent in ordinary construction processes make the presence of e.g. welds, nuts, or bolts inevitable. Consequently, knowledge about connections is essential in any design situation. In the design of protective structures against small-arms bullets, thin plates made of steel are widely used due to their advantageous combination of strength, hardness, ductility, and relatively low price compared to most other armor materials [6]. However, when areal mass is taken into account, high-strength aluminum alloys can rival the ballistic properties of high-strength steels [7,8].

Welding is a common and effective joining procedure, but welding of aluminum generates a zone which may be weak relative to the base material. This zone is known as the heat affected zone (HAZ), and it may cause a so-called ballistic window in protective structures. Usually material strength governs ballistic performance [6,9], so special attention is required in the design of welded aluminum protective structures.

The strength and work hardening of Al–Mg–Si aluminum alloys can be predicted with reasonable accuracy by nano-scale material models [10–13]. The application of such a model was shown by Johnsen et al. [14], where the stress-strain behavior of four different

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heat treatments (tempers) of the wrought aluminum alloy AA6070 was determined with a nanostructure model, NaMo. The model was able to predict the yield strength and work hardening of the different tempers. Subsequently, mechanical non-linear finite element simulations, using the yield strength and work-hardening determined with NaMo as input, accurately described the ballistic behavior. This correlation suggests that employing the predictive capabilities of nano-scale material modeling in combination with tools that can provide thermal histories in all material points due to welding can dramatically reduce the need for expensive and time-consuming experimental programs.

Computational models which were designed to incorporate elements of the manufacturing process for conventionally or friction-stir welded steel and aluminum protective structures have also been of interest for several years [15–17]. These techniques are often called through-process modeling. In some cases, the ballistic behavior is included in the model [18–21].

There are two main objectives of this paper. First, we investigate how welding affects the ballistic properties of aluminum extrusions of various thicknesses through an extensive experimental program for 10 mm, 20 mm and 30 mm thick profiles, including tension tests for the 10 mm and 30 mm profiles; hardness measurements of the base material, HAZ, and weld for all thicknesses; and ballistic impact experiments. In the ballistic tests, armor piercing (AP) bullets are fired at the welded test specimens at various distances from the weld center line. Second, and most important in this study, a purely numerical method is demonstrated. The numerical approach is performed independently from the experiments. Hence, the experimental results are only used for validation purposes in this part of the paper. The heat distribution from multi-pass welding is calculated numerically by the thermal finite element program WELDSIM [22]. Results from selected points in these analyses are used as inputs to NaMo [23] to determine the yield strength and hardening behavior of the material as functions of distance from the weld center line, before the non-linear finite element code IMPETUS Afea Solver [24] is employed to solve the impact problem itself. All the calculations can be done without carrying out a single experiment.

Sections 2 and 3 present an experimental program in which the material processing, welding procedure, material testing, and ballistic testing are carried out to obtain an experimental basis for comparison with, and validation of, the subsequent numerical results. Section 4 outlines the numerical scheme and provides a description of the use of WELDSIM, NaMo and IMPETUS Afea Solver. In Section 5 the numerical predictions are presented, discussed, and compared to the experimental results. The main observations and conclusions are summarized in Section 6.

2. Material

2.1. Material processing and welding

Extruded 10 mm, 20 mm and 30 mm thick profiles made of AA6082-T6 were investigated in this study. The measured chemical compositions of the extrusions provided by Hydro Aluminium and the composition window of AA6082 are shown in Table 1. Due to the varying profile thicknesses, the artificial aging to obtain the peak strength temper T6 varied. The 10 mm extrusion was held at 175 °C for 5 h and 30 min, while the 20 mm and 30 mm thick extrusions were held at 185 °C for 5 h and 10 min.

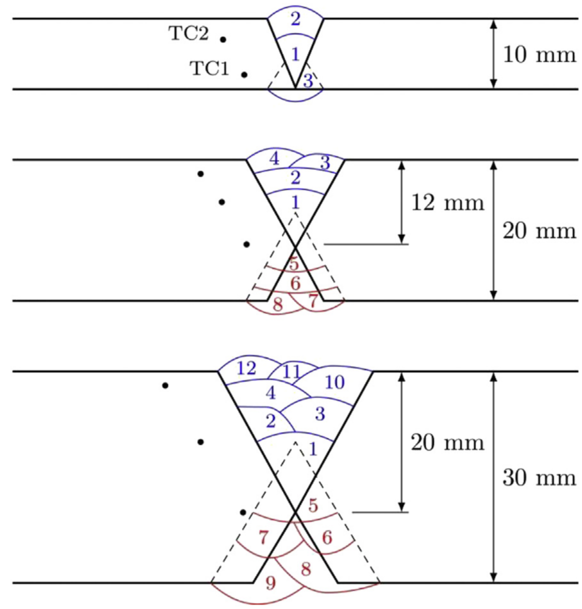

Fig. 1. Numbering of the weld-seams in the multi-pass welding procedure. Placements of the thermocouples are indicated with dots.

The flat extruded profiles were automatically welded to each other with MIG welding at Marin Aluminium AS. Precautions were taken to ensure that the welding process was in accordance with EN 1090-3 [25]. Numbering of the various weld seams in the multi-pass welding procedures is shown in Fig. 1. In all welding procedures the temperature of the HAZ was measured to be below 100 °C before the next weld seam was initiated. The welding consumable was a Safra 5183 welding wire designed for high corrosion environments such as ship constructions and offshore applications ($\sigma_{0.2} \geq 125$ MPa [26]). Complex thermal histories were introduced during welding due to the application of three weld passes for the 10 mm profile, eight for the 20 mm profile, and twelve for the 30 mm profile. The temperature-time histories were measured by thermocouples. The placement of these thermocouples is shown in Fig. 1, while selected results from the temperature measurements are shown later in the paper.

2.2. Material testing

Three tensile tests of the base material were performed in both the extrusion direction (0°) and the cross-weld direction (90°) for the 10 mm and 30 mm thick extruded profiles. Two typical curves from the 0°-direction are shown in Fig. 2. A Zwick Roell 30 kN tensile testing machine was used with a crosshead velocity of 1.2 mm/min. This corresponds to an initial strain rate of 5×10^{-4} s^{-1} for the circular test specimens with an initial

Table 1
Chemical composition of the various profiles, and composition window for AA6082 in wt-%.

	Si	Mg	Mn	Fe	Ti	Zn	Cu	Cr	Al
Measured – 10 mm profile	0.93	0.60	0.55	0.18	0.011	0.002	0.008	0.011	Balance
Measured – 20 mm profile	0.99	0.63	0.56	0.17	0.018	0.006	0.025	0.011	Balance
Measured – 30 mm profile	0.97	0.63	0.54	0.16	0.013	0.004	0.004	0.013	Balance
Composition window AA6082	0.7–1.3	0.6–1.2	0.4–1.0	0.50	0.10	0.20	0.10	0.25	Balance