International Journal of Impact Engineering 95 (2016) 17–34

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Development of high crush efficient, extrudable aluminium front rails for vehicle lightweighting

Christopher P. Kohar [a], Amir Zhumagulov [a], Abhijit Brahme [a], Michael J. Worswick [a], Raja K. Mishra [b], Kaan Inal [a,*]

[a] Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON N2L3G1, Canada
[b] General Motors Research & Development Center, Warren, MI 48090, United States

ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form 1 April 2016
Accepted 18 April 2016
Available online 19 April 2016

Keywords:
Aluminium
Crush tubes
Optimization
Crashworthiness

ABSTRACT

Understanding the behaviour of automotive structural components is essential for vehicle weight reduction and passenger safety. In this study, a novel framework is developed to design an optimized front rail that maximizes crash energy absorption characteristics. The new design is coupled with material and process development to provide a component with superior energy absorption and strength characteristics that is commercially sustainable. Simulations of the extrusion crush behaviour are performed using the anisotropic Barlat et al. (2003) Yld2000 yield functions. The simulations are compared to the dynamic crush results for this extrusion. The size of the structure is optimized using the response surface methodology, using artificial neural networks metamodels and simulated annealing optimization techniques. The specific energy absorption (SEA) is used as a single optimization objective function for maximizing energy absorption and minimizing mass. An analytical relationship that relates the SEA function to the crush efficiency is derived to show that a single optimization function parameter may be sufficient for mass minimization. Analysis is performed to identify key extrusion operational parameters and the wall thickness is identified as the most important parameter to control during extrusion.

1. Introduction

Implementation of lightweight aluminium alloys to fabricate automotive components has become integral to achieve vehicle mass reduction. Major energy absorption structures of automobiles, such as the front rails, rockers, pillars, etc. are excellent candidates for mass reduction with aluminium because they contribute substantially to the overall vehicle weight. Such components must be designed to exhibit energy dissipation comparable to that of current steel components in the event of a collision to meet vehicle safety requirements [1].

The crush behaviour of lightweight structures has been a widely studied topic in literature for several decades. Initial work by Wierzbicki, Abramowicz, and Jones led to the development of mechanics of axial crush based on analytical models that closely reflected experimental data for steel components [2–11]. With improvements in computational technology over time, commercial nonlinear finite element packages, such as LS-DYNA, have been utilized to predict the energy absorbing response of complex structures from other materials. Langseth et al. [12,13] used commercial finite element software to simulate and validate the quasi-static and dynamic crush response of aluminium extrusions using an isotropic von Mises hardening model. They compared their simulation results with experimental crush data from various aluminium structures and found good agreement. Kim [14] combined experimental observations and finite element results to manually optimize the topology of a single piece multi-cellular aluminium extrusion. Mayer et al. [15] explored the effects of artificial aging to improve the quasi-static crush behaviour of multi-cell extrusions from AA6061 and AA6063 aluminium alloys. They observed that after a specific aging time, the crush performance of the AA6063 structure remained unchanged at an optimal performance.

In recent years, the use of optimization software that utilizes artificial intelligence and machine learning algorithms has served as a valuable tool in improving the crashworthiness performance (see e.g. Refs. 16–23). Multiple finite element simulations have been performed on the axial crush response of the structures using isotropic hardening models. Mathematical models have been developed to predict the crash response of finite element simulations as a function of input parameters. Machine learning and optimization techniques have been applied to such models to increase the crash performance by varying the topology and topography of the structure. This approach, known as structural optimization through the response surface methodology [24], has been employed to

* Corresponding author. Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, ON N2L3G1, Canada. Tel.: +1 519 888 4567 Ext. 38114; Fax: +1 519 885 5862.
E-mail address: kinal@uwaterloo.ca (K. Inal).

http://dx.doi.org/10.1016/j.ijimpeng.2016.04.004
0734-743X/

optimize the shape of honeycomb structure to maximize the energy absorption [25]. Esfahani et al. [25] have used numerous finite element simulations to calibrate a mathematical model and perform optimization using a hybrid-adaptive simulated annealing algorithm. Through this technique, they have been able to optimize the energy absorption of the structure while minimizing mass.

Currently commercially available 7xxx series aluminium alloys have very high specific strength that is comparable to that of steel and allow for easy substitution for conventional steel applications. The main drawbacks of 7xxx series alloys continue to be their poor corrosion resistance, low extrudability leading to high cost and recycling limitations in multi-material vehicle applications. From consideration of the extrudability and recycling, the 6xxx series alloys are superior to 7xxx series for mass-production application. However, the 6xxx series alloys have a lower specific strength compared to the 7xxx series alloys. A technological platform capable of optimizing the shape of the profile to meet energy absorption requirements with the lower strength 6xxx extrusion is presented in this study.

An aluminium extrusion profile with multi-cellular structure as a crush structure is an excellent candidate for further optimization because the wall thickness – a parameter that strongly correlates with mass as well as energy absorption – can be easily controlled and varied in the manufacturing process. A multi-cavity extruded tube made from an AA7xxx alloy that satisfies the design constraints and meets the crush energy absorption needs for front rail applications in a current production vehicle is then taken as a benchmark for optimization of 6xxx structure in this investigation. The benchmark tube is experimentally crush tested using a dynamic sled apparatus to obtain the experimental energy absorption response. AA6063-T6 extrusion with the same profile is crushed under the same experimental conditions for comparison. The commercial FE software, LS-DYNA, is used to simulate the crush behaviour of the AA6063-T6 structure using measured material anisotropy and high strain rate behaviour data from the extruded tubes as input. The simulation results are compared to experimental results to validate the FE model. New multi-cellular extrusion profiles are developed through FE modelling, manufactured, sled-tested and crush simulation results are compared with experiments. The size of the new multi-cellular extrusion is optimized using the response surface methodology, to further improve the energy absorption characteristics, while the topology and topography is held constant. The sizing of the extrusion is varied using the commercial optimization package, LS-OPT. The specific energy absorption, which maximizes the energy absorption and minimizes the mass, is selected and evaluated as a single optimization objective.

2. Experiments

Fig. 1 presents the cross-section of the baseline extrusion profile. Commercially available AA6063 billets were extruded using a commercial extrusion press and the extruded rails were artificially aged to a T6-temper. Fig. 2 shows a new multi-cellular four-cell hexagon structure, referred to as UWR4 extrusion profile, which was also extruded. The multi-cellular topology was developed through an optimization of the number of crush elements within the profile envelop (for further details on this approach, the readers are refer to Refs. 14, 25, and 26). Each aluminium extrusion profile was cut to a length of 464 mm for crush experiments. Table 1 presents the length, mass and other data for the tested materials. Table 2 lists the chemical composition of the extruded tubes.

Quasi-static uniaxial tensile tests, in accordance with ASTM-E8, were performed using specimens cut along the extrusion direction of the baseline profile to explore the variation in the mechanical behaviour in eleven different locations (as indicated in Fig. 1). The resulting true stress–true strain curves are shown in Fig. 3. Some variation existed in the T6-temper mechanical responses. In particular, two stress–strain responses exceeded the average response, due to the variation in the cooling rate of the internal webs (numbered 7 and 9 in Fig. 1) during the extrusion process. An average stress response was fit to a power-law hardening model [27]

$$\bar{\sigma} = K\left(\varepsilon_0 + \bar{\varepsilon}_p\right)^n \quad (1)$$

where $\bar{\sigma}$ is the effective yield stress, $\bar{\varepsilon}_p$ is the total plastic strain, ε_0 is the total elastic strain, K is the strength coefficient and n is the work hardening exponent. Table 3 lists the representative parameters.

In the experimental work of Hsu and Jones [28] for extruded AA6063-T6, it was reported that this alloy exhibits moderate strain rate sensitivity. Thus, moderate strain rate tensile testing was performed for strain rates of 10/s and 100/s. Miniature dog-bone specimens were cut from the extrusion and pulled in uniaxial tension using a hydraulic intermediate strain rate apparatus. The details about the experimental apparatus and testing procedure are similar to that described in Bardelcik et al. [29]. The power law plasticity relation, coupled with the Cowper–Symonds strain rate sensitivity [30], was used to characterize the strain-rate sensitivity. This relates the effective stress, $\bar{\sigma}$, to the total plastic strain, $\bar{\varepsilon}_p$, and it is written as

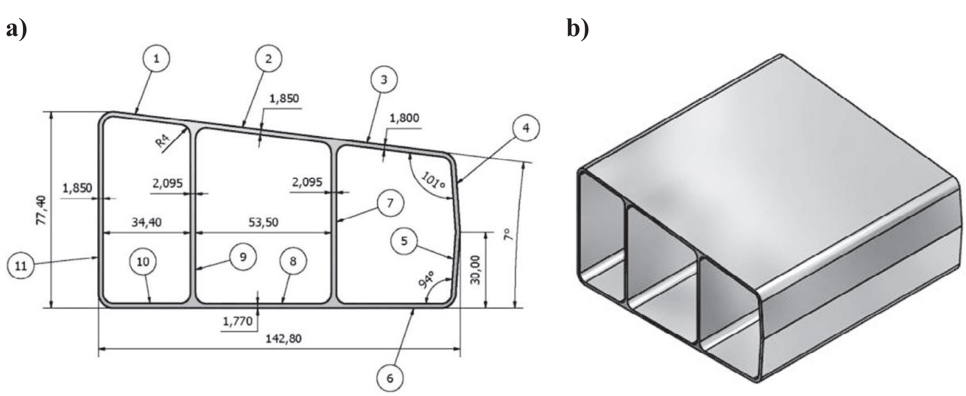

Fig. 1. (a) Cross section and (b) isometric view of baseline extrusion profile.