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Crushing analysis and multi-objective optimization of a cutting aluminium tube absorber for railway vehicles under quasi-static loading

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ABSTRACT

To explore a diverse number of energy absorption methods, this paper presents an investigation of a cutting aluminium tube absorber for railway vehicles. A quasi-static cutting experiment on an aluminium tube is conducted. The finite element models presented in this study are based on experimental tests, and good agreement is achieved between the experimental and finite element results. It is shown that the cutting aluminium tube absorber presents a stable deformation mode. The chip morphologies of the numerical simulation and experimental test results are coincident, demonstrating that failure criteria defined under the material model are effective. Moreover, a parametric study is performed using finite element models under quasi-static loading. It is found that the cutting depth t, cutting depth w and cutting angle α have a distinct effect on the energy absorption (*EA*), mean crushing force (*MCF*) and peak crushing force (*PCF*) of the absorber. Sobol' sensitivity analysis is employed to analyze the effects of the design parameters (t, w, and α) on the objective responses (*EA* and *PCF*) based on a polynomial response surface model. It is found that at a larger cutting depth, the increases in *EA* and *PCF* are larger. Additionally, to optimize the crushing performance of the absorber, a multi-objective optimization is applied to achieve the maximum *EA* and minimum *PCF* values. The results show that *EA* increases with increasing *PCF* and at the optimal point B (*EA* = 78.29 kJ, *PCF* = 341.88 kN), and thus, a balance between *EA* and *PCF* is obtained.

1. Introduction

As passenger safety requirements become more stringent, researchers are paying greater attention to issues of vehicle crashworthiness. The energy absorption structure of a train is critical, as the impact kinetic energy of a train is dissipated by the orderly plastic deformation of an energy absorption structure. In general, the crush performance of an energy absorption structure is closely related to the deformation mode, to the damage mechanism and to loading modes [1,2]. An energy absorption structure offering higher energy absorption efficiencies can absorb more impact kinetic energy during an accident. Therefore, the investigation of the crush performance of energy absorption structures is of central importance to issues of vehicle crashworthiness and passenger security.

Thin-walled structures are widely used as energy absorbing structures in automobile manufacturing, railway vehicle design, aerospace and other fields. Thin-walled structures are characterized by a stable deformation mode and exhibit high levels of energy absorbing efficiency under axial crushing. Due to differences in the material, wall thickness, cross-section, length, load and boundary conditions of thin-walled structures, many deformation modes of thin-walled structures have been observed during crushing, including axial folding [3], bending [4], inversion [5], expansion [6], splitting [7] and flattening [8]. Each energy dissipation mechanism is characterized by certain features.

With the continuous development of materials and structures, new energy absorption structures and modes of energy dissipation applied to vehicles have been widely studied by researchers. Zhang et al. [9] presented a new energy absorption structure referred to as a retractable tube and analysed the force displacement curve and deformation mode through numerical simulation. They found that the proposed tubes offer significantly higher levels of energy absorption efficiency than traditional invertubes. Gao et al. [10] analysed the collision performance of square tubes with diaphragms via finite element simulations, and their numerical results show that square tubes with diaphragms undergo a relatively stable crushing process. Alavi Nia et al. [11] studied the energy absorption tendencies of multi-cell tubes through theoretical analyses, numerical simulations and experimental tests. It was found that the energy absorption capacities of the proposed multi-cell square section are approximately 227% greater than those of a simple section.

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Nomenclature

L	length of the aluminium tube
R	radius of the aluminium tube
T	thickness of the aluminium tube
α	die angle
t_0	original thickness of the test specimen
b_0	original width of the test specimen
b_t	width of grip section of the test specimen
l_o	original gauge length of the test specimen
l_c	parallel length of the test specimen
l_t	overall length of the test specimen
l_g	length of grip section of the test specimen
R	radius of fillet of the test specimen
S_0	original section area of parallel length of the test specimen
t_e	reduced thickness of the fracture cross section
b_e	reduced width of the fracture cross section
l_e	reduced length of the fracture cross section
W	displacement in the Y direction in the simple shearing
U	displacement in the X direction in the simple shearing
γ	shear strain
γ_{max}	maximum shear strain
A	yield stress of Johnson-Cook material model
B	strain hardening constant of Johnson-Cook material model
n	strain rate sensitivity coefficient of Johnson-Cook material model
c	strain hardening index of Johnson-Cook material model
σ_y	flow stress
σ_m	hydrostatic stress
σ_e	equivalent von Mises stress
σ_1	first principal stress
σ_2	second principal stress
σ_3	third principal stress
T	stress triaxiality
ε_1	first principal strain
ε_2	second principal strain
ε_3	third principal strain
$\bar{\varepsilon}_f^p$	equivalent plastic fracture strain
t	cutting depth
w	cutting width
α	cutting angle

Kashani et al. [12] proposed adding a small square tube to an ordinary square tube to form a double square tube and improve energy absorption performance and that the crashworthiness of a small diamond-type square tube is superior to that of a parallel arrangement. Foam aluminium and aluminium honeycombs, which can fully utilize structure spaces to improve the material utilization ratios, are added to thin-walled structures to improve the crushing performance of these structures [13,14]. Cheng and Altenhof [15] studied the force displacement curves and energy absorption characteristics of a square aluminium tube through a cutting experiment and showed that load displacement responses are nearly constant when cutting steel plates. Jin et al. [16–19] conducted AA6061-T6 tube cutting tests and showed that the cutting force increases rapidly to a constant. It was found that cutting widths considerably influence the cutting forces, while the tube lengths and lubrication conditions have a limited influence on the cutting forces and energy absorption levels. Second, the failure modes of AA6061-T6 tubes subjected to axial cutting forces in a single blade and in multiple blades were studied through experimental tests, and an analysis model of cutting forces for AA6061-T6 tubes was created to compare test data. Finally, factors influencing the cutting energy absorption of aluminium tubes subjected to axial loading were studied through quasi-static and dynamic experiments, and the results showed that axial cutting forces grow more pronounced with increasing number of blades and with increasing tube diameters and wall thicknesses. Gao et al. [20] presented an active–passive integration energy absorber based on metal cutting deformation and investigated the energy absorption performance of aluminium and steel tube cutting. Dong et al. [21] proposed a new type of energy absorption structure that uses the splitting and bending behaviors of steel plates and analysed the deformation mode of steel plates subjected to axial crushing through numerical simulations and experimental tests. They then conducted a parametric study through a numerical simulation and found that plate thicknesses, die angles, die widths and distances between steel plates and baffles have significant effects on the energy absorption levels.

Due to the multiple design parameters and target responses that characterize the design process of the energy absorption structure, complex modeling processes are involved, and design goals are conflicting. Therefore, multi-objective optimization algorithms have been widely applied in the design of energy absorption structures. Marzbanrad and Ebrahimi [22] studied a dynamical crush process observed through circular hollow tubes of AA6060-T4 and T5 alloys through simulations and employed multi-objective crashworthiness optimization to address the maximization of the objective functions. Costas et al. [23] studied a frontal crash absorber via surrogate-based multi-objective optimization techniques whereby the thicknesses of different parts, the geometries of cross-sections and the offsets of reinforcement parts were used as design variables. The results show improvements in the Specific Energy Absorption and Load Ratio levels, which are considered as contrasting objective functions, of almost 50% relative to the original design. Li et al. [24] studied the energy absorption of functionally graded foam (FGF)-filled tubes under multiple load conditions. It was found that the impact angle and gradient exponent have a significant effect on the crashworthiness of FGF-filled tubes. Then, a multi-objective optimization algorithm was applied to improve the crashworthiness of FGF-filled tubes. Xu et al. [25] studied the crash performance of a newly designed gradual energy-absorbing structure subjected to impact loads through experimental and numerical simulations. To maximize energy absorption levels while minimizing the peak crushing force (*PCF*), the Non-dominated Sorting Genetic Algorithm was used for the multi-objective optimization of the thickness distribution of the gradual energy-absorbing structure. Fazilati and Alisadeghi [26] studied the multi-layer configuration of a hexagonal metal honeycomb energy absorber using a multi-objective optimization technique. To investigate the effects of cell sizes, foil thicknesses, heights and absorber face areas on the maximization of energy absorption capacities and on the minimization of impact shock, a factorial experiment and response surface method was used to solve the optimization problems. Acar et al. [27] performed a multi-objective optimization of the crushing of tapered thin-walled tubes with axisymmetric indentations to maximize the crush force efficiency and specific energy absorption levels. Sun et al. [28] investigated the crushing behaviors of functionally graded tubes and the effects of gradient patterns with different thicknesses on the crushing performance using the Non-dominated Sorting Genetic Algorithm. It was found that the FGT tube is superior to its counterparts of uniform thickness in terms of overall crushing behaviors.

A review of research conducted on energy absorption structures shows that few relevant studies have examined metal cutting deformations used as energy absorption tools for vehicles. Therefore, we propose a new cutting aluminium tube absorber for railway vehicles. A finite element model for cutting aluminium tube absorbers is established based on quasi-static cutting tests. Numerical results are analysed using the force-displacement curves of deformation models. In addition, absorber fracture behaviors and energy dissipation mechanisms