International Journal of Impact Engineering 95 (2016) 72–88

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Crashworthiness design of quenched boron steel thin-walled structures with functionally graded strength

Liang Ying [a], Xi Zhao [a], Minghua Dai [b], Sizhu Zhang [a], Ping Hu [a,*]

[a] School of Automotive Engineering, Dalian University of Technology, Dalian 116024, China
[b] School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China

A R T I C L E I N F O

Article history:
Received 10 December 2015
Received in revised form 28 April 2016
Accepted 2 May 2016
Available online 4 May 2016

Keywords:
Thin-walled structure
Functionally graded strength (FGS)
High strength boron steel
Crashworthiness
Multi-objective optimization

A B S T R A C T

Thin-walled structures have been widely used as energy absorbers in industries such as automobile, shipping and aerospace. Different from recent well-studied columns consisting of aluminum, this paper introduced a kind of quenched boron steel column formed by hot stamping technology, with wall strength varying along the axial direction with a specific gradient, i.e. functionally graded strength (FGS). These FGS structures are found to have higher crashworthiness in terms of peak crash force (PCF) and specific energy absorption (SEA) compared with the counterpart structures with uniform strength (US). Based on a series of numerical simulation results, it revealed that the crashing behavior of FGS columns is significantly affected by both the strength gradient and the strength in the impact end. To optimize the crashworthiness (PCF and SEA) of the FGS structures, multi-optimization based on different metamodeling techniques such as response surface method (RSM), radial basis function (RBF) neural network model, kriging (KRG) model and optimization algorithm of non-dominated sorting genetic algorithm (NSGA-II) are performed. Pareto fronts of several alternative thicknesses were obtained to provide guidance for the FGS column design and give a good insight into actual crashing engineering. It is interesting to find that the gradient exponent is taken as the main design variable when the PCF is restricted below a certain value while the parameter of steel strength in impact end will be taken as the main design variable on the contrary. The comparison of Pareto fronts between the FGS and US columns showed that the FGS columns enhance the SEA and lower the PCF concurrently. Furthermore, among the three metamodeling techniques, the RSM models are proven to be the most suitable approach for the crashworthiness optimization of FGS structure.

1. Introduction

Energy saving, environmental protection and security have become the core of current manufacturing. As an energy absorber in crashworthiness applications such as trains, cars, ships, aeroplanes and other high-volume industrial products, the thin-walled structures have been widely used to ensure crash safety due to their lightweight, low cost and high energy absorption. In early studies, steel was extensively used for thin-walled structures because of its low price and excellent ductility [1]. But nowadays, there is a growing demand for the development and application of lightweight structures due to the increasing importance of mass reduction.

Accordingly, more and more studies have been focused on aluminum alloy columns. Studies are conducted by means of analytical, numerical and experimental methods. Outcomes or findings include circle-, square- and hat-shaped cross-sections of columns that affect crashing performance [2,3], and also an efficient method to increase the columns' energy absorption by filling them with foam [4–7] of polymer or metal was presented. Besides that, some have focused on thin-walled structures with tapered shape [8,9] and multiple cells [10–13]. In recent years, after Gupta et al. and Maharsia et al. [14,15] have fabricated "functionally graded" syntactic foam and found its remarkable effect in improving energy absorption, an increasing number of researchers have been devoted to this research field. Cui et al. [16–17] developed a functionally graded foam (FGF) material that contains micro-scale cells varying continuously in a predefined manner and revealed that the FGF materials were better candidates for improving energy absorbing behaviors than conventional uniform foams. Yin [18–19] found that both the dynamic peak crash force (PCF) and specific energy absorption (SEA) were determined by the density gradient of material. Subsequently, the functionally graded foam with different gradient form was filled in various thin-walled structures [20], while the non-filled columns were also designed into different gradient forms, for instance functionally graded thickness [21–23], to make people better

* Corresponding author. School of Automotive Engineering, Dalian University of Technology, Linggong Road 2#, Ganjingzi District, Dalian 116024, Liaoning Province, China. Tel.: +86 13842821969; Fax: +86 0411 84702775.
E-mail address: pinghu@dlut.edu.cn (P. Hu).

http://dx.doi.org/10.1016/j.ijimpeng.2016.05.001
0734-743X/

understand the effect of the gradient on crash response and obtain optimum crashing behavior.

Apart from the focus on the crashing behavior of aluminum or the foam filled aluminum thin-walled structures as mentioned above, the thin-walled structures consisting of steels with high strength have also been presented. Though the specific strength of aluminum is higher than the conventional mild steel and can lead to higher SEA and weight efficiency, more and more advanced high strength steels (AHSS) with much higher specific strength turn up, such as dual phase (DP) steel [24–26] and transformation induced plasticity (TRIP) steels [27], due to development in technology. As an AHSS steel, the quenched boron steel formed by hot stamping technology possessing an ultimate stress as high as 1600MPa [28–30] is supposed to be superior in crashing behavior due to its higher specific strength.

As the hot stamping technology developed, researchers have further invested in research of the tailored property of the hot stamping steel [31,32], i.e. improve the technic to produce an entire sheet with graded strength. Nishibata and Kojima [33] investigated the effect of the cooling rate on the hardness and strength of quenched boron steel and found the basic mechanism and method to achieve tailored property. Bardelcik et al. [34] austenitized and quenched the boron steel blanks with forced air at five different cooling rates ranging from 14 to 50 °C/s and established a constitutive model as a function of strain, strain rate and as-quenched Vickers hardness. Meanwhile, a strain-based fracture criterion for quenchable boron steel was presented and calibrated based on the experiment carried out by Eller et al. [35]. The above analysis established a solid foundation for the product design with gradient strength since the established material models can be directly or indirectly used by other researchers in numerical analysis.

Besides the above researches about mechanical property, more studies have been carried out on how to manufacture the boron steel structure with graded strengths, and several technologies have been brought up such as the stage cooling by forced air [36], the bypass resistance heating of blank and the tailored tempering process using heated and cooled tools [32,37,38]. Among them, the tailored tempering process is the hottest technology that has been studied by many researchers in many aspects. Based on this process, parts with graded strengths have been successfully manufactured by R. George [32,39], and low conductivity tools were proven to be better than that with high conductivity in consideration of the robustness [36]. Furthermore, a numerical model of the tailored tempering process was developed by Tang et al. [38], which can use the commercial FE code Forge™ to accurately predict the part Vickers hardness distribution and microstructural evolution before they are manufactured, so the temperature distribution on tools can be reverse predicted according to the strength distribution on designed part. Besides, Mori et al. [40,41] have developed a hat-shaped tailored die and successfully formed the AHSS parts with gradient strength distribution using bypass resistance heating technology, too. The above research basis has provided us with confidence to design structures with functionally graded strengths (FGS); however, very limited studies on crashworthiness design of thin-walled FGS structures have been conducted so far. Along with the development of the tailored hot stamping technology, the optimal FGS columns can be manufactured in the future.

To obtain FGS thin-walled structure with optimum crashworthiness, it is essential to understand the energy absorption characteristics of FGS structures in comparison with those conventional US ones. FGS structures have changing wall strength along the axial direction in a specific gradient and allow changing steel strength on either end of the columns. The wall strength varies throughout the axial depth in an ascending or descending exponential gradient, in which an exponent is used to determine the pattern. Therefore, the purpose of this study is to seek the best possible strength gradient exponent for crashing performance, together with the steel strength on column's impact end as it would obviously affect the PCF value in axial crash directly.

To achieve the above objective, numerical simulations of FGS columns configured with different gradient exponents and steel strength on impact end were conducted in LS-DYNA by using a five-level full factorial design of experiments (DoE) method, and three different wall thickness of 1.0 mm, 1.5mm and 2.0mm were employed. Metamodeling techniques as response surface method (RSM), radial basis function (RBF), kriging (KRG) model and an advanced experiment design method used for optimization of composite structures were employed to establish the relationship between objectives of PCF, SEA and variables of gradient exponent m and steel strength s on the impact end of structure. To minimize the PCF and maximize the SEA, multi-objective optimizations for the FGS columns based on optimization algorithm of non-dominated sorting genetic algorithm (NSGA-II) were performed.

2. High-strength steel thin-walled structures with functionally graded strength

2.1. Quenched boron steel with tailored properties

The thin-walled sections in this study consist of quenched boron steel BR1500HS, which can obtain different material properties when quenched at different cooling rates [33,34,42,43]. The original microstructure of BR1500HS steel is the compound of ferrite and pearlite. The chemical composition and mechanical properties of as-received BR1500HS are shown in Table 1.

According to the CCT (continuous cooling transformation) diagram [33,44] of quenched boron steel, the steel's microstructure will change to different phases such as ferrite, pearlite, bainite, martensite or their mixture after being quenched at different cooling rates. As a consequence, different micro-hardness and yield strengths are then obtained. Bardelcik et al. [34] revealed that there is a linear relationship between the Vickers hardness and percent area fraction of martensite and bainite present in the quenched specimens. Based on the true stress versus effective plastic strain curves obtained from a series of tensile tests at four strain rates of 0.003 s^{-1}, 1.0 s^{-1}, 85 s^{-1} and 1075 s^{-1}, a constitutive model as a function of strain (ε), equivalent strain rate ($\dot{\varepsilon}$), and as-quenched Vickers hardness (HV) is developed as shown in equation (1)

$$\sigma = f(\varepsilon, \dot{\varepsilon}, HV) = \left[A(HV) + \left[(B(HV) - A(HV)) e^{\left(-\frac{\varepsilon}{C(HV)}\right)} \right] \right] [1+\dot{\varepsilon}]^{D(HV)} \quad (1)$$

Table 1
Chemical composition and mechanical properties of as-received BR1500HS.

Material	Chemical composition (mass fraction, %)							Mechanical properties		
	C	Si	Mn	P	B	Cr	Cu	YS (MPa)	TS (MPa)	EI (%)
BR1500HS	0.22	0.25	1.23	0.008	0.004	0.20	0.03	485.0	612.0	22.0

YS, yield strength; TS, tensile strength; EI, elongation.