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Development of high-performance energy absorption component based on the structural design and nanocrystallization

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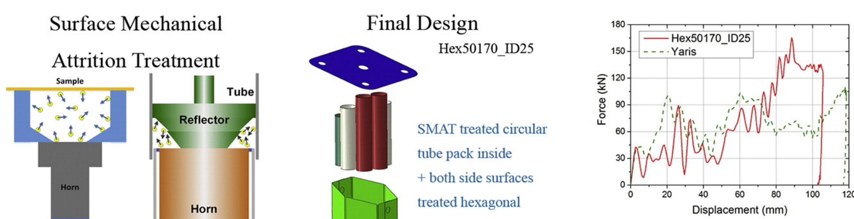
HIGHLIGHTS

- Surface Mechanical Attrition Treatment was utilized to enhance the material properties of energy absorption components.
- The newly-designed crash box is more light-weighted, with lower initial peak force and higher energy-absorption ability.
- A new Surface Mechanical Attrition Treatment system was developed to treat the interior surface of tube structures.

GRAPHICAL ABSTRACT



Configuration	Yaris	HEX50170_ID25
Weight (kg)	1.945	1.090
Specific energy (kJ/kg)	3.9	6.9
Peak Force (kN)	100.9	89.4
Compression Ratio	72%	61%

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ABSTRACT

Over the past decades, to meet the ever-increasing energy-saving and environmental-friendly needs, light-weight vehicles, e.g., electric cars, have been widely advocated. Due to significant deterioration in the capability of energy dissipation, crashworthiness enhancement becomes again the most critical issue for the light-weighted vehicles. However, the design based on conventional structure has been more difficult, and the employment of high-strength materials induces much higher cost. To achieve both large safety margin and low cost, this study implemented both material enhancement and structure optimization in the energy absorber design. Since most light-weight structures involve thin-walled frames, the surface mechanical attrition treatment (SMAT), able to induce nanostructures in metals for strength enhancement without sacrificing ductility, is the perfect choice. Based on the structure of energy absorber, SMAT technology was intensively improved to take full advantage of the excellent performance of the advanced steel material and fulfill real-life application. Structure optimization was also explored through extensive experiments and numerical simulations. The final products was examined by real tests, and the results revealed that it was lighter, stronger and have high-safety impact levels compared to similar products on the present market as expected.

1. Introduction

The large and dynamic plastic deformation of structures was extensively studied in the past aiming to improve the crashworthiness of crucial structures e.g., the frame of vehicles, the subfloors of helicopters, or the highway parapet etc. and to better protect the

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occupants from catastrophic events of impacts, crashes, collisions, and explosions [1,2,3]. These studies have led to the application of various energy absorption structures, which are characterized by the thin-walled features that are bent and folded to absorb mechanical energy and retain the crushing force in a reasonable low level. Typical energy absorption structures are concluded in the monographs [4,5]. However, in the context of the world's advocacy of saving energy consumption, the significant reduction in propulsion requires light-weight structures, which generally leads to the significant deterioration in the capability of energy dissipation [6,7,8]. Therefore, crashworthiness design becomes again the most critical issue.

While the developments of these energy absorbers in the past decades are based on the in-depth investigation of dynamic structural response, little attention is paid to effect of micro- or nano-scale material structures on the macroscopic structural response. It is worthwhile noticing that the capability of energy absorption of the material is not fully utilized in these energy absorbers, because dynamic plastic deformation is through localized bending and stretching, which leaves the majority of the materials unused. The advance in materials science has demonstrated that by altering the micro- or nano-scale structures, the materials, with same chemical composition, could demonstrate large variation of yield and ultimate stresses. It is then intriguing to utilize such strength variation in the design of new crashworthiness structures, to exploit more material in energy dissipation and lower the manufacturing cost.

The enhancement of mechanical properties of metals, which was realized in our laboratory by the surface mechanical attrition treatment (SMAT) [9,10], is attributed to the refinement of grain size and the introduction of nanostructures in the subsurface layers. The principle of SMAT is based on the random plastic deformation induced by the vibration of spherical balls with mechanical vibration system or using high-power ultrasound. Recent development indicates SMAT is a very efficient technique to generate the nanostructure with thicker layers. The published uniaxial tensile tests have shown that the yield stress of the SMAT metals can be doubled or even tripled over the benchmark one without significant reduction in the ductility [11]. Comparing with other grain refinement technologies, e.g. the severe plastic deformation method (SPD) or electro-deposition (ED), SMAT is much easier to be implemented and potentially the most useful one for industry [12,13]. Along with its low cost, SMAT is really a synthesis, processing, and manufacturing approach for commercially affordable nanostructure. In this study, we are going to investigate the application of SMAT in the design of structure for maximize its energy absorption capability.

In automobile industry field, the impact type is generally classified into two categories: high-speed impact and low-speed impact [14,15]. During high-speed impact, the loading force and loading energy are both very large, and the whole framework of the vehicle, including anti-collision beams, side beam, pillars and crash box, etc., will undergo severe large deformation. Crash box can only absorb a minority of the whole impact energy. The design target for bearing high-speed impact is to increase the energy-absorption capacity of front engine compartment and reduce the risk of passenger injuries. On the contrary, low-speed impact contains lower amount of energy and passenger safety is not the key focus. Thus, the design target is to reduce the risk of key auto parts damages so as to decrease the maintenance costs. Crash box, as the main energy absorption structure during the process of low-speed impact, is investigated and optimized in the present study and only the low-speed impact response is considered hereinafter.

The objective of this study is to integrate the SMAT technology in the lightweight structural design. Such integration is to exploit the capability of the enhancement of SMAT for optimization of energy absorption structure.

2. Material and methods

2.1. Material

According to our previous research results, plate-shaped stainless steel 304 (SUS304) has an excellent property enhancement on strength and ductility after SMAT [16,17]. In the present study, SUS304 was chosen as the main research subject used for the study.

2.2. SMAT treatment

The main technology used in this study was SMAT that has been well recognized to be the one of the most promising micro-structural refinement technology implantable to industry [9,10]. The material enhancement by SMAT is due to the grain-size refinement, which is subject to the Hall-Petch empirical relation that the yield stress is inversely proportional to the square root of the grain size. Although the thickness of the effective grain-refinement layer is only in the order of several hundred of micrometers, it has been proved that SMAT is very effective to increase the yield stress and bending strength of sheet metals of 1–2 mm thickness [16,17]. Moreover, the combined effects of the refined grains and compressive residual stresses in the subsurface layers and the coarse-grained substrates retained a sufficient ductility of the material for the practical applications. These research outcomes demonstrate that SMAT is especially suitable for strengthening of thin-walled structures, which play the major role in the crashworthiness structures. Fig. 1 shows SMAT machine and the treatment process.

In order to check the mechanical properties of the SUS304 materials, uniaxial tensile tests will be performed on both the untreated and treated parts of the material.

2.3. Uniaxial tensile test

Uniaxial tensile test was carried out to obtain the constitutive relations of the steel material. It was performed using a universal testing machine MTS Alliance RT/30 as shown in Fig. 2. The samples were cut out from different kinds of treated tubes and plates.

2.4. Drop-hammer test

The drop-hammer dynamic impact test on crash box was conducted in Suzhou Automotive Research Institute, Tsinghua University, China. The impact mass was 207 kg, and the drop height was set as 4 m. The weight underwent a free fall process and directly impacted on the crash box. The bottom flange plate of the crash box was firmly fixed by screws on the base of the test stand, so the kinetic energy of the moving weight was absorbed only by the tube body. The formal test setting and a simple flow chart are shown in Figs. 3 and 4.

3. Models and designs

Design is a vital part of this study and the crashworthiness ability of different configurations of energy absorption element is considered through adjusting fabricating parameters, geometry parameters and structure parameters, i.e.. The design process is just the process of adjusting parameters and find out the optimal collection of different parameters with best energy-absorbing property.

However, the whole design work only resorting to experimental approach would be an impossible mission due to huge amount of workload. Thus, the structure design will be also carried out through numerical simulations with consideration of different factors, including the cross section shape, trigger, junctions, inner filler, loading conditions, SMAT-treatment scheme and so forth. It should be emphasized that the experimental and simulation work cannot be separated from each other in the structure design procedure. And ABAQUS was adopted in this study for its powerful computation ability.