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Manufacturing process and mechanical properties of a novel periodic cellular metal with closed cubic structure

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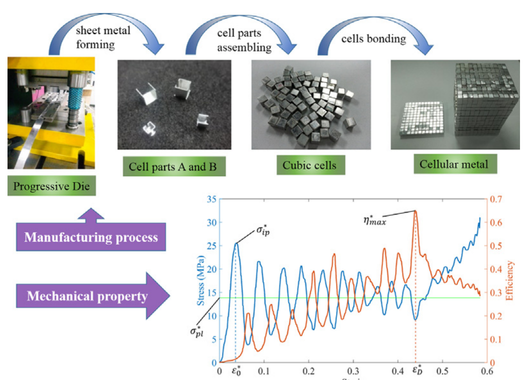
HIGHLIGHTS

- A novel periodic cellular metal with three-dimensional closed cubic structure was developed and presented.
- The presented cellular metal is manufactured initially by sheet metal forming, and then by cells bonding.
- The mechanical properties of the presented cellular metal were investigated by compressive and impact experiments.
- The presented cellular metal shows a sound energy absorbing performance and a great potential used for passive safety.

GRAPHICAL ABSTRACT



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ABSTRACT

Cellular metal is an ideal energy absorbing material which is extensively used in passive safety area. This paper investigates the manufacturing process and mechanical properties of a novel periodic cellular metal with three-dimensional closed cubic structure. The manufacturing process of this kind of cellular metal is unconventional because it is obtained initially by sheet metal forming, and then by cells bonding. In this work, two methods including gluing and laser welding are introduced for bonding the cells. By the gluing method, various cellular metals with irregular/regular topological cellular structures can be automatically manufactured via an innovative device which is originally put forward in this work. By contrast, the laser welding method is more suitable for fabricating the cuboid cellular metal blocks. Meanwhile, the cellular metal fabricated by laser welding comparing with by adhesive owns better mechanical performance because there are not any heterogeneous layers between the cells. In order to investigate the mechanical properties of the cellular metal fabricated by laser welding, a series of quasi-static compressive and drop weight impact experiments were carried out. The experimental results demonstrate that the presented cellular metal possesses a sound energy absorbing performance and a great potential used for passive safety.

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1. Introduction

As light-weight materials with high stiffness and strength, cellular metals have attracted a lot of attentions in the past two decades. They have distinctive properties that make them attractive for many engineering applications such as light-weight structural sandwich panels, energy absorption devices, heat sinks and so on. So far, many kinds of cellular metals have been developed mainly including metal foam, honeycomb and lattice truss. According to cellular connectivity, cellular metals can be classified as closed-cell and open-cell structures. The former internally consist of a mass of independent and disconnected holes or tissues; by contrast, the latter contain plenty of interconnected and permeable cellular structures. On the other hand, according to cellular regularity, cellular metals can be classified as non-periodic and periodic cellular structures. The former contain numerous randomly distributed unit cells or irregular cellular structures. Metal foam is the most common non-periodic cellular metal [1]. The periodic cellular metals, as the name suggests, are made up of orderly arrangement cellular structures or regular unit cells. Currently, most of the periodic cellular metals belong to the open-cell structures, including honeycomb and lattice truss structures. The fundamental properties of cellular metal were systematically introduced by Gibson and Ashby in their book [2]. Furthermore, they summarized the manufacturing processes and proposed a design criterion for cellular metal in another book [3]. Their work laid a sound foundation for the study of cellular metal to some extent.

Up to now, numerous methods for manufacturing cellular metals have been developed. Especially, various manufacturing processes of metal foam are well-developed at present, which normally can be classified in terms of state of matter in which the metal is processed — solid, liquid, gaseous or ionized [4]. Besides, some aluminum metal foams also can be fabricated by powder metallurgy process [5]. At present metal foam can be manufactured and obtained in industrial scale production [6]. However, since the manufactured cellular size and shape cannot be accurately predicted and controlled, the mechanical properties of the metal foam are hard to be deeply analyzed and evaluated theoretically.

As for the manufacturing methods of the periodic cellular metal, Wadley et al. [7–9] have been taking researches in this field for many years. Specifically, Wadley [10] gave an overview of various cellular metals manufacturing, and subsequently he also [11] introduced various manufacturing processes for the periodic cellular metal including honeycomb, corrugated topologies and lattice truss structures and so on. In particular, honeycomb is a common form of periodic cellular metal containing a large number of honeycomb cells which are stacked in two-dimensional (2D) plane. In addition to metals, there are some honeycombs fabricated by other materials. Liu et al. [12] manufactured the metallic glass honeycombs by thermoplastic forming. Shim et al. [13,14] expanded honeycomb structures by soft materials. Lattice truss is another form of periodic cellular metal, in which the cells are stacked in three-dimensional (3D) volume. Jung et al. [15] proposed a continuous system for fabricating a metallic sandwich plate with a 3D truss core. In recent years, with the advancement of additive manufacturing (AM) technology [16], AM become a feasible method for manufacturing periodic cellular metals especially for the lattice structures. For example, Ramirez et al. [17] successfully fabricated periodic open-cellular copper structures by AM using electron beam melting; Williams et al. [18] presented a layer-based AM process of metallic cellular materials via 3D printing; Pinto et al. [19] combined AM with lost-wax casting to fabricate periodic structure and took some experiments to study their compressive properties; Yan et al. [20] also successfully fabricated lattice structure by selective laser melting. However, besides quite time consuming, the cost of the AM process for the cellular metal is currently so high that it is confined to laboratory study, let along industrial scale production.

With regard to the mechanical properties, Gibson [21] published a review in 2000 to summarize the mechanical behavior of metallic foams including both of the open-cell and the closed-cell structures. Subsequently, Song et al. [22] investigated the dynamic crushing behavior and the energy absorption capacity of 3D closed-cell cellular metal based on some basic parameters such as relative density, impact velocity, strain hardening and cell irregularity. Li et al. [23] studied the crushing response of both impacting and supporting sides of 3D closed-cell foam under impact loading. The aforementioned researches mainly focused on the metal foam, or more specifically, on the 3D closed-cell cellular metal. In fact, these researches were mostly carried out by means of simulation analysis of FEA. However, since the structural model used in FEA is quite different and inconsistent with the actual foam due to cellular inhomogeneity, the analytical accuracy for the mechanical properties of the metal foam could not be guaranteed. Therefore, in our opinion it would be preferable to take advantage of some experimental measures besides simulation. In addition to metal foam, metal matrix syntactic foams as similar purpose material attract quite a lot of attention nowadays. Since they are on the borderline between metal matrix composites and metal foams, they can demonstrate outstanding specific mechanical properties which were investigated in detail based on compressive experiments by Orbulov et al. [24–26].

Concerning the mechanical properties of the periodic cellular metal with honeycomb structures, a lot of researches primitively focused on the dynamic crushing behavior [27,28]. Besides honeycomb, some other kinds of 2D cellular metals were also investigated. For example, Ju et al. [29–31] investigated some compliant cellular structure with extremely high positive and negative Poisson's ratios. With regard to the mechanical properties of the lattice truss structures, Gorny et al. [32] investigated the deformation and failure mechanisms in lattice truss structures obtained by selective laser melting. Wadley et al. [33] studied the impact response of aluminum corrugated core sandwich panels. Until now, however, few studies have been reported in the literatures about the periodic cellular metal with 3D closed cell structures.

This paper presents a novel periodic cellular metal with 3D closed cubic structure which can serve as an ideal cushioning or energy absorbing material. The manufacturing process of this kind of cellular metal is unconventional because it is carried out primarily by sheet metal forming and then by cells bonding. In this work, two methods are proposed for bonding cells, i.e. gluing and laser welding. Although the gluing method was discussed in our previous studies [34–36], an innovative conceptual device for automatically bonding cells by gluing method is introduced in this paper. However, since the presented cellular metal is developed for cushioning/energy absorbing, this work mainly focuses on the cellular metal obtained by laser welding due to its better mechanical properties. Accordingly, a series of quasi-static compressive experiments and drop weight impact experiments were carried out for an in-depth investigation into the mechanical properties of the cellular metal fabricated by laser welding. The experimental results have guiding significance for practical application of this kind of cellular metal in passive safety area.

2. Cellular structure and manufacturing process

2.1. Cellular structure

The presented periodic cellular metal is made up of numerous cubic cells which are stacked and bonded in a 3D volume based on a certain topological structure. Every cubic cell is hollow, closed and relatively small, so it would be very difficult to fabricate directly. Therefore, the cubic cell is divided into two separate counterparts for the sake of easier fabricating, as showed in Fig. 1. The two counterparts of the cell are individually formed by sheet metal stamping, which are called cell part A and cell part B respectively. Once they are formed, they will be directly assembled and locked together into an integrated cubic cell by a certain gripping force from cell part B to cell part A. From Fig. 1, it can be seen that there are four rectangular contact regions between them. So supposing that the width and height of every contact region are