Tensile Behavior and Performance of Syntactic Steel Foams Prepared by Infiltration Casting

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Abstract: Syntactic steel foams (SSFs) were prepared by low-pressure infiltration of molten ASTM CF-8 cast austenitic stainless steel into randomly and densely packed Al₂O₃ hollow spheres. The microstructure of the SSFs was characterized by scanning electron microscopy and energy dispersive spectrometry. Using dumbbell-shaped specimens, the density of the as-cast SSFs is measured in the range from 3.33 to 3.64 g/cm³ and their ultimate tensile strength from 83.1 to 97.6 MPa. No significant chemical reaction was detected between the fillers and matrix. The quasi-static uniaxial tensile deformation of the syntactic foams underwent elastic deformation, plastic deformation, and then a failure stage, showing similar tensile behavior to plastic bulk metals but different behavior to common metal foams. From the good ductility of the metal matrix, a clear macroscopic plastic deformation was observed before the ductile fracture of the syntactic foams. A constitutive relationship of the SSFs under uniaxial tensile loads has been proposed.

Keywords: tensile behavior; syntactic steel foams; composite structure; deformation mechanism; infiltration casting

1. Introduction

As a subgroup of the class of closed-cell metal foams, syntactic metallic foams consist of the addition of hollow spheres to a metallic matrix. They combine the strength of the metallic matrix with the excellent energy absorption capacity of foam materials [1,2]. Lightweight alloys, such as aluminum [3–9] and magnesium [10–13], are commonly used matrix materials in metal matrix syntactic foams (MMSFs), but systems with zinc [14–16], titanium [17–19], and iron [20–23] matrices have also been reported. Benefitting from a variety of advantages, including low weight, high specific strength, high specific stiffness, vibration damping, and high energy absorption, MMSFs are widely used in the aerospace, transportation, packing, defense, and construction industries [24]. Because the main load mode for MMSFs is compression, the quasi-static and dynamic compressive properties of MMSFs have been widely investigated in recent years by experimental [7,14,25–27] and numerical simulations [8,28,29]. For practical engineering applications, however, MMSFs often need to face multiple load conditions. Under low-speed impact loads, for example, a tensile-bending failure is produced. These engineering applications put forward a clear need to study the tensile behavior, failure mechanisms, and constitutive relations of MMSFs. MMSFs show significant differences in their compressive and tensile behaviors, but little attention has thus far been paid to the latter of these [30,31].

Manakari et al. [11] investigated the tensile behavior of magnesium syntactic foams reinforced by hollow silica nanospheres. Characterization of the tensile properties at room temperature suggested that, compared with pure magnesium alloy, the increased addition of hollow spheres led to progressive improvement in both tensile yield strength (TYS) and ultimate tensile strength (UTS). The tensile failure strain (TFS), conversely,
exhibited a declining trend. In research by Weise et al. [32], the tensile performance of 316L stainless steel syntactic foams reinforced by glass microspheres, which was expressed in terms of yield strength, UTS, and failure strain, decreased significantly with an increase in microsphere content. Tao et al. [33] examined the effect of ceramic microsphere size in an Al alloy matrix. Tests on that system showed that the tensile strength was insensitive to the size of the reinforcement sphere and all the samples failed in a brittle manner, with plastic deformation in only a limited number of cases. It was proposed that, because of the unique structures of MMSFs, low tensile strength and brittle fracture are inherent weaknesses of these materials under tensile loads. The tensile deformation behavior of iron syntactic foam reinforced with hollow glass spheres was examined by Cho et al. [34]. In their research, a three-dimensional finite element model was developed using the representative volume element (RVE) approach and random sequential absorption (RSA) algorithm. Lin et al. [35] compared the tensile failure behavior of cenospheres/Al syntactic foams with Al-Mg alloys and pure Al; the fractography showed that under tensile loads, the cenospheres in the pure Al syntactic foam were released from the matrix and the tensile loads were applied entirely to the metal matrix. In contrast, the cenospheres in Al-Mg alloys syntactic foam were well-bonded and susceptible to lamellar tearing. Peroni et al. [36] investigated the dependence of the tensile properties on the strain rates in invar matrix syntactic foams. With a strain rate change from $10^{-3}$ s$^{-1}$ to $10^3$ s$^{-1}$, the tensile tests suggested that the TYS and UTS both increased with the increase in strain rate. In addition, the strain rate sensitivity was found to be more significant for tensile loads compared with compressive loads [36].

Tensile behavior is one of the most important testable items in the manufacturing of structural materials, and the TYS, UTS, and TFS are important parameters that reflect the material properties. To date, there are few published studies that have focused on the tensile properties and failure mechanism of MMSFs, especially for high melting point iron-matrix syntactic foams. In the present work, SSFs were fabricated through an infiltration casting method with ASTM CF-8 cast austenitic stainless steel as the metal matrix and reinforced with Al$_2$O$_3$ hollow spheres. The tensile properties, microstructure deformation, and failure mechanism were studied. Moreover, a tensile constitutive relationship has been proposed. To the best of our knowledge, no research studies on the tensile behavior of high melting point SSFs have been published previously.

2. Materials and Methods

2.1. Materials

ASTM CF-8 cast austenitic stainless steel (CHAOFEI, Donggaun, China) was used as the matrix material, and the chemical composition of the matrix is listed in Table 1. The choice of matrix material was important for making full use of the MMSFs, and ASTM CF-8 cast austenitic stainless steel has good mechanical properties, weldability, and corrosion resistance. More importantly, compared with other steels, ASTM CF-8 cast austenitic stainless steel has better fluidity performance, which can effectively prevent the metal melt from stopping the flow before the infiltration is completed.

Table 1. Chemical composition of ASTM CF-8 cast austenitic stainless steel and alumina hollow spheres used in this work (in wt %).

| Material       | Chemical Composition (wt %) |
|----------------|-----------------------------|
| ASTM CF-8      | C  Si  Mn  Cr  Ni  Fe       |
|                | 0.02 1.0 1.6 19.1 10.2 balance |
| Alumina HS     | Al$_2$O$_3$  Na$_2$O  Fe$_2$O$_3$  SiO$_2$  Others (MgO/K$_2$O/CaO) |
|                | 99.2 0.19 0.16 0.18 0.27    |
For filler material, the particles should have sufficient fire resistance and chemical stability to withstand the erosion of high-temperature molten steel during the infiltration casting. Additionally, the reinforcement needs to be light enough to minimize the overall density of the syntactic foam. The Al$_2$O$_3$ hollow spheres that can be used under 1800 °C do not react with the steel matrix, making them a good choice for producing syntactic foams [37]. Three grades of Al$_2$O$_3$ hollow spheres, with average diameters of 3.11 mm, 3.97 mm, and 4.79 mm, were applied in the present work to investigate the effect of hollow sphere size on the tensile properties of the SSFs. The purchased hollow spheres were subjected to flotation treatment with alcohol and acetone before being used as the filler to remove any damaged spheres, then sieved into different particle sizes. The standard deviation was less than 10% of the average diameter in all three groups. The chemical composition of the alumina hollow spheres is provided in Table 1.

2.2. Methods

The SSFs investigated in this study were produced by a low-pressure infiltration casting method. The specific preparation methodology has been described elsewhere [21]. A schematic of the infiltration is illustrated in Figure 1. To summarize, the Al$_2$O$_3$ hollow spheres were packed randomly and densely in a graphite crucible mold, and the mold was preheated in a vacuum medium-frequency induction furnace. Meanwhile, the matrix material, ASTM CF-8 cast austenitic stainless steel, was melted at 1550 °C and poured into the preheated mold under a vacuum operated at less than 10 Pa. After solidification, the syntactic foams were machined into the desired shape for characterization.

![Figure 1. Schematic illustration of the infiltration and the tensile specimen.](image)

2.3. Characterization

The density of the syntactic foams was determined by dividing the mass by the macroscopic volume. The as-cast SSFs were ground and polished to observe the microstructure of the interface between the filler and the metal matrix using scanning electron microscopy (SEM, Gemini 300, ZEISS, Oberkochen, Germany) equipped with an energy dispersive spectrometer (EDS) for composition analysis.
Quasi-static uniaxial tensile tests were performed on an DNS 300 test machine (CIMACH, Changchun, China), with a crosshead speed of 1 mm/min, and each single test was halted at the point at which the sample broke. There is limited literature focused on the tensile properties of metal foams, meaning that the relevant testing standard is also limited. In the present work, the structure of bulk materials for tensile behavior characterization was taken as a reference, and a dumbbell-shaped tensile specimen was designed in accordance with ASTM-E8 plate standard [38], as shown in Figure 1. To avoid the influence of pore size on the stability of the tensile properties, the minimum size of the sample cross-section was at least seven times the outer diameter of the Al₂O₃ hollow sphere [39]. Because the largest hollow sphere used in this study had an average diameter of 4.79 mm, all tensile specimens were machined into dumbbell shapes 260 mm in length and with a middle cross-section size of 40 × 40 mm.

3. Results and Discussion

3.1. Physical Properties and Structure

The density values of the as-cast SSFs and the corresponding bulk metal matrix are listed in Table 2. With the increase in the average diameter of the hollow spheres used in the preparation, the density of the SSFs increased slightly.

Table 2. The density of the produced SSFs and the matrix, the volume, and mass fraction of HS and matrix.

| Sample   | Average Diameter of HS (mm) | Density (g/cm³) | V_HS (%) | V_m (%) | M_HS (%) | M_m (%) |
|----------|-----------------------------|-----------------|----------|---------|----------|---------|
| SSFs -1  | 4.79                        | 3.64            | 56.29    | 43.71   | 6.35     | 93.65   |
| SSFs -2  | 3.97                        | 3.40            | 59.66    | 40.34   | 7.46     | 92.54   |
| SSFs -3  | 3.11                        | 3.33            | 60.62    | 39.38   | 7.75     | 92.25   |
| Bulk metal matrix | —                      | 7.8             | —        | 100     | —        | 100     |

A macro photograph and microstructure images of the Al₂O₃ hollow spheres and the SSFs are shown in Figures 2 and 3, respectively. It can be seen from Figure 2a–c that the particles used in this study were almost perfectly spherical. Surface defects, however, were also detected on the sphere wall, with smaller micropores embedded inside the sphere wall and larger microspores extending through the entire sphere wall, as indicated by the arrows in Figure 2b–d. The commercially available Al₂O₃ hollow spheres, which were produced by a blowing method, have uneven sphere wall thicknesses in the range of tens to hundreds of micrometers. During the pressure infiltration process, a thin sphere wall with micropores may crack under pressure, resulting in infiltrated particles.

As shown in Figure 3a, the Al₂O₃ hollow spheres were distributed uniformly in the metal matrix. Close inspection of the surface of the SSFs revealed that some hollow spheres were infiltrated by the molten metal entirely (the red dashed circles in Figure 3a). A possible reason for this phenomenon may be the good fluidity of the metal matrix used in this study. For example, the infiltration was completed under pressure and the good fluidity may have allowed the molten metal to infiltrate into the inner cavities of the hollow spheres through small pores in the sphere wall (as shown in Figure 2b,c). In addition, the cracks caused by pressure in the sphere wall also provided a path for the molten metal to infiltrate into the hollow spheres.

Figure 3b–d shows that the hollow spheres and the metal matrix appeared to bond well, and a clear interface can be observed between the hollow spheres and metal matrix in the SSFs. As illustrated in Figure 3b, some casting voids were found around the interface between the matrix and sphere wall, which were possibly the result of incomplete infiltration and shrinkage cavities caused by the difference in the thermal conductivity between
the hollow spheres and metal matrix, and the low wettability between the metal melt and alumina HS. The presence of the voids indicated that the combination between the hollow spheres and the matrix was by simple physical adhesion.

Figure 2. Macro photograph (a) and SEM images (b–d) of Al₂O₃ hollow spheres.

Figure 3. Macro photograph (a) and SEM images (b,c) of SSFs. Magnification of the interface structure (d) and the corresponding EDS map (e–i).
The chemical composition distribution near the metal–hollow sphere interface was determined by EDS scanning. In Figure 3e–i, the main chemical elements in the matrix material and the filler spheres—Al, O, Fe, Ni, and Cr—are distinguished by differently colored spots in the SEM micrographs; the compositions of Al, O, and Fe changed drastically at the interface between the matrix and hollow spheres. The O-rich region and the Al-rich region appear to be uniform in the hollow sphere side, in which the dominant composition was Al₂O₃, as shown in Figure 3ef. Figure 3gh show in detail the enrichment of Fe and Ni, which were both detected to be concentrated at the surface of the metal matrix. The distribution of all dominant elements in the SSFs shows a clear change at the metal matrix–hollow sphere interface, except for Cr. In Figure 4, a uniform distribution of Cr can be seen in the entire scanned area, with a possible explanation for this being surface pollution during the production of the SSFs. Furthermore, the diffusion of Cr in Al₂O₃ under high-temperature (above 1500 °C) casting conditions may have played a part, as was previously reported by Jia et al. [40].

**Figure 4.** (a) Tensile stress–strain curve of SSFs and typical aluminum foam (the inner image [41]). (b) Comparison of the UTS of different types of metal foams [11,32,36,38,42–47].
3.2. Tensile Properties

Under quasi-static uniaxial tensile loads, the engineering stress–strain curves of the SSFs with different densities are plotted in Figure 4a. Regardless of the syntactic foam density, all curves exhibited three distinctive stages under tensile loads: initial linear elastic deformation, followed by a plastic deformation, and eventual failure. More specifically, the engineering stress–strain curve of the SSFs was in the linear elastic deformation stage during the first section of stretching, i.e., the stress was proportional to the strain, and when the external force was removed, the SSFs returned to their original size. During this period of tensile behavior, the engineering stress–strain relationship conformed to Hooke’s law. As the tensile load was increased, the syntactic foam underwent a plastic deformation. When the stress exceeded a certain value (TYS), the engineering strain increased at a faster rate than the increasing stress. In this period of stretching, the deformed specimen was not able to return to its original state when the external load was removed; the deformation of the SSFs included plastic deformation and deformation strengthening; and the slope of the stress–strain curve was reduced. In the third stage of stretching, the stress continued to increase with the increase in strain until it peaked (the UTS) when the syntactic foam reached its breaking point. From Figure 4a, the SSFs with the greatest density, which were reinforced by the largest $\text{Al}_2\text{O}_3$ hollow spheres, gave the highest UTS. As proposed by Tao et al. [33], the mechanical bonding between the metal matrix and the sphere is not very strong. Consequently, the tensile load is largely borne by the metal matrix. The dense contacts between adjacent microspheres, which result from a high volume percentage of microspheres in the syntactic foams, provide many sites for the initiation of fracture under tensile loads. As a result, the syntactic foams showed brittle failure under tensile stress. The larger the filler spheres used, the fewer the contacts between adjacent spheres that formed. Meanwhile, the larger gaps and pores between spheres resulted in stronger metal pillars in the syntactic foams, leading to increased UTS. As shown in Figure 5a, the syntactic foams with densities of 3.40 g/cm$^3$ and 3.33 g/cm$^3$, which were reinforced by medium-sized and the smallest hollow spheres, respectively, gave relatively lower UTS values (83.8 MPa and 83.1 MPa, respectively). Meanwhile, the syntactic foams that were reinforced by the largest hollow spheres gave the greatest density (3.64 g/cm$^3$) and significantly higher UTS (97.6 MPa).

The tensile behavior of the SSFs under uniaxial tensile loads showed similar characteristics to the bulk ASTM CF-8 cast austenitic stainless steel, i.e., a plastic plateau accompanied by deformation and strain hardening was observed. This differed from the tensile behavior observed in the common metal foam. As pictured by the inner image in Figure 4a, the linear elastic deformation of aluminum foam only occurred with very small strain before the aluminum foam entered the plastic deformation stage [41]. There was no obvious TYS point or plastic plateau during the whole deformation. At a small engineering strain (less than 0.3%), tensile or shear cracks emerged in the cell wall of the aluminum foams, then cracks spread rapidly inside the metal foams, forming a macroscopic fracture, and the load-bearing capacity of the foams dropped significantly.

The tensile data collected from the literature of different types of metal foams are given in Figure 4b. It is evident from this figure that the tensile strength of conventional steel foam maintains at a low level (less than 10 MPa) [43–45]; in contrast, the tensile strength of the syntactic metal foams is much higher. In a variety of metal matrices, from steel [32,38], invar [36,42], or light metal magnesium [11], the introducing of reinforcement particles (hollow spheres or glass microspheres) gave the tensile strength of the metal foam a significant enhancement. It is worth noting that the sizes of reinforcement particles also have a great influence on the UTS of the syntactic metal foam. Of particular interest is that the tensile failure strain of the syntactic steel foam prepared in the present work is significantly greater than that of A. Rabiei et al. [38]. A plausible explanation is that we chose a ductile steel (ASTM CF-8 cast austenitic stainless steel) to be the matrix, which greatly expands the application of high melting point syntactic foam in tensile loads.
As mentioned in Section 3.2, the tensile load was largely borne by the metal matrix in the syntactic foams. Under tensile loads, the engineering stress and the deformation were concentrated on the weakest part of the SSFs. Before the final failure, microcracks were observed on the walls and edges of the pores, which burdened high stress on the syntactic foams. Figure 5b shows that, at small strain, several microcracks formed along the regular arrangement of spheres. With an increase in engineering strain, a crack band began to sprout, and the entire deformation was concentrated in this zone (Figure 5c). Subsequently, several pores broke first in the crack zone, and further deformation caused the main crack to develop and propagate along the weakest path in the SSFs until the final fracture occurred. The ultimate failure mechanism depended on the ductility of the metal matrix in the syntactic foam. The fracture occurred, most commonly, far from the fixture, and the direction of the fracture was perpendicular to the tensile load.

The investigated SSFs underwent obvious macroscopic plastic deformation before fracture, where a clear ductile fracture was observed. This ductile fracture was dependent mainly on the matrix material. Compared with other steel matrices, the ASTM CF-8 cast austenitic stainless steel used in this research has good ductility, which was confirmed by the tensile tests of the as-cast syntactic foams. Figure 5e–h shows the fresh surface of the tensile fracture obtained using SEM, where many micropits can be seen covering the cross-section. These pits, known as dimples, were indicative of ductile fracture in the foams [42]. Some microparticles were found in the dimples, and the formation of the dimples was closely related to the existence of these small particles.

As illustrated by Wilsdorf [48], any heterogeneity in a material can nucleate cracks through the production of a stress concentration or strain localization, and breaking bonds of any type is the fundamental precursor to nucleation of a crack. As shown in Figure 5i, during the elastic–plastic deformation of the SSFs under tensile loads, as the stress was concentrated, the continuous breaking of atomic bonds led to atomic separation and crack growth from incipient cracks. After that, transgranular and intergranular microcracks and microcavities emerged at the matrix–hollow sphere interface and in the steel matrix, respectively, as shown in Figure 5j. The opening microcrack propagated along the direction

![Figure 5](image-url)
perpendicular to the tensile loads into the matrix of the SSFs. Meanwhile, the microcavities could coalesce and form egg-shaped ellipsoids. When these separated ellipsoids connected with each other, a so-called cup–cone fracture surface formed (ductile dimple), as shown in Figure 5e,k. It should be noted that melted beads were detected at the end of the ruptured dimple. A likely explanation for this is that because the ductile dimples were stretched to very thin thicknesses (nano-dimension range), there was suppression of the melting point of the metal matrix [49]. At the moment the SSFs were fractured, the high strain rates produced melted beads at the end of the thin dimples, as illustrated in Figure 5l.

3.4. Tensile Constitutive Relationship

When a structural specimen is loaded by an external force, its mechanical behavior is determined by the deformation mechanism of the sample. Under tensile loads, for example, the specimen will undergo elastic deformation, followed by plastic deformation as the load increases, then fracture. The equation describing the deformation response of these structural components to the external loads is termed the constitutive relationship, which includes several characteristic material parameters, such as the UTS and elastic modulus.

The TYS was obtained using the 0.2% strain offset method. Figure 6 represents the tensile stress–strain curves of MMSFs with different densities and the corresponding 0.2% strain offset line. Table 3 summarizes the tensile properties of the syntactic foams and the corresponding bulk material. Studies have shown that the relative density and the internal cell structure will significantly affect the mechanical properties of syntactic foams under tensile loads. In general, the greater the relative density, the greater the failure stress of the syntactic foams, and strong syntactic foams commonly benefit from a uniform distribution of micropores in the metal matrix.

Table 3. Comparison of tensile properties between SSFs and solid metal.

| Sample     | HS Diameter (mm) | \( \rho \) (g/cm\(^3\)) | Max Load (kN) | UTS (MPa) | TYS (MPa) |
|------------|------------------|---------------------------|---------------|-----------|-----------|
| SSFs -1    | 4.79             | 3.64                      | 161.546       | 97.6      | 52.3      |
| SSFs -2    | 3.97             | 3.40                      | 139.790       | 83.8      | 50.7      |
| SSFs -3    | 3.11             | 3.33                      | 138.656       | 83.1      | 49.6      |
| Bulk metal matrix | —                | 7.8                       | —             | 485       | 205       |

Under uniaxial tensile loads, the UTS of SSFs is determined by its relative density, and a simplified relationship is given as [50]:

\[
\frac{R_m}{R_s} = C_1 \left( \frac{\rho}{\rho_s} \right)^m
\]  

(1)

where \( \rho \) and \( \rho_s \) are the density of the syntactic foams and the corresponding bulk metal, respectively. \( R_m \) and \( R_s \) represent the UTS of the syntactic foam and bulk metal, respectively. \( C_1 \) and \( m \) are constants related to the geometric structure of the MMSFs, which must be determined in this study. With the data listed in Table 3, three groups of \( R_m/R_s \) and \( \rho/\rho_s \) values could be calculated. Subsequently, the \( C_1 \) and \( m \) were determined as 0.85 and 1.9, respectively. Finally, the constitutive relationship of the SSFs under uniaxial tensile loads can, therefore, be given as:

\[
\frac{R_m}{R_s} = 0.85 \left( \frac{\rho}{\rho_s} \right)^{1.9}
\]  

(2)
Figure 6. Cont.
Figure 6. Tensile stress–strain curves of SSFs with different densities, (a) 3.64 g/cm³, (b) 3.40 g/cm³, (c) 3.33 g/cm³.

As shown in the Figure 7, the equation can fit well with the present experimental results.

Figure 7. The plot of Equation (2) and the correlation factor of the SSFs.

4. Conclusions

ASTM CF-8 cast austenitic stainless steel syntactic foams reinforced by Al₂O₃ hollow spheres were produced by an infiltration casting method. The microstructure and quasi-
static uniaxial tensile tests were studied in the as-cast syntactic foams without further heat treatment. The deformation and failure mechanism of syntactic foams under tensile loads were also analyzed. The quasi-static uniaxial tensile deformation of the investigated syntactic foams underwent three stages: elastic deformation, plastic deformation, and failure. The deformation in the SSFs developed and propagated uniformly under uniaxial tensile loads, demonstrating similar tensile behavior to plastic bulk metals and different tensile behavior than metal foams. Under the tensile loads, the deformation was concentrated in the weakest part of the syntactic foam. Microcracks were found at the cell walls and edges of high-stress pores before the final failure, and the failure mechanism depended on the plasticity (or ductility) of the metal matrix of the syntactic foam. The fracture most often occurred far from the fixture, and the direction of the fracture was perpendicular to the tensile load. A macroscopic plastic deformation was observed before the ductile fracture of the syntactic foams. The metal matrix used in this study, ASTM CF-8 cast austenitic stainless steel, has good ductility, and ductile fractures of the as-cast syntactic foams under tensile loads were observed. Finally, a constitutive relationship for the SSFs under uniaxial tensile loads has been proposed.

Author Contributions: Conceptualization, Q.Y.; Data curation, C.F. and Y.D.; Formal analysis, Y.F.; Funding acquisition, C.F. and E.W.; Investigation, Y.M. and Q.Y.; Methodology, Y.F.; Project administration, Y.D.; Visualization, E.W.; Writing—original draft, Y.M.; Writing—review and editing, Q.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Strategic Priority Research Program of Chinese Academy of Sciences (XDB28000000, XDB33000000) and the Fundamental and Applied Basic Research Fund of Guangdong (2021A1515110333).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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