Mechanisms of strain rate effect of metal foams with numerical simulations of 3D Voronoi foams during SHPB tests

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Abstract

Metal foams were usually prepared and tested as light-weight and efficient energy absorption materials. Controversial results among different tests and numerical simulations show that the mechanisms of strain rate effect of metal foams are not clear yet. To study the main mechanisms of strain rate effect of metal foams during split Hopkinson pressure bar (SHPB) tests, numerical simulations were carried out by FEM, in which metal foams were simulated with 3D Voronoi models. In these simulations, the matrix material of metal foams is assumed to have no strain rate sensitivity, which helps to determine the strain rate effect of metal foams clearly. The numerical simulations show that metal foams' specimens still exhibit some strain rate sensitivity even the matrix material without strain rate sensitivity. Further quantitative analysis reveals that effects of inertia and localized deformation of metal foams are two main causes to induce the strain rate sensitivity of metal foams.

Keywords: Metal foams, Strain rate effect, Inertia, Localized deformation,3D Voronoi model

Introduction

Metal foams, as light-weight and highly effective energy absorption materials, are wildly employed as protective materials to resist impact loading (Gibson1997). With the development and application of metal foams, an accurate measurement of its dynamic properties become especially important. A split Hopkinson pressure bar (SHPB) (Kolsky1949) is the most common device to measure dynamic properties, with which the characteristic of compression deformation, energy absorption and strain rate sensitivity of metal foams have been intensively investigated. However, the experimental results showed that strain rate effect of metal foams were inconsistent and divided into two categories: the apparent strain rate sensitivity(Mukai1999, Dannemann2000, Paul2000 and Mukai2006) and the independent strain rate sensitivity (Deshpande2000 and Hall2000). Under dynamic conditions, strain rate effect of metal foams have attributed to the effect of strain rate sensitivity of cell wall's materials (Deshpande2000), micro-inertial effects (Paul2000, Deshpande2000 and Paul2000) and the effect of compressed air pressure in closed-cell foams (Gibson1997 and Deshpande2000). For these factors are too difficult and complex to be quantitatively measured in tests, which factor plays a vital role in strain rate sensitivity also is not clear yet.

A series of SHPB tests indicated the compressed deformation of metal foams were observed to be non-uniform(Tan2005, Cady2009,Edwin Raj2009 and Shen2010), especially in high speed impact tests. The strain distribution of aluminum foams were quantitatively analyzed and showed the maximum localized strain can be more than 100% greater than the average values, specially the maximum strain occurred on the front end of specimens under middle and high speed impact tests(Yang2013). SHPB technique is based on the assumption of one-dimensional wave propagation and stress equilibrium in the bars, which is simply assumed that uniform deformation occurred on specimens. However, the tests results showed that the deformation of metal foams were not well satisfied the assumptions of SHPB under dynamic conditions. The obviously localized deformation will likely affect the results.

For complexity of dynamic tests and micro-structure of metal foams, analysis of mechanisms of strain rate effect, especially quantitatively analysis, will be a challenge and significance. In present work, we have carried out numerical simulation by FEM, in which metal foams were simulated with 3D Voronoi models, to analyze the mechanisms of strain rate effect of metal foams during split Hopkinson pressure bar tests.

Numerical simulation

Meso-structures of metal foams, as shown Figure.1, with the characteristic of random spatial distribution, are very complex. For an excess of units and complex contact properties, it is too difficult to build the finite element model of metal foams according to the real meso-structure , especially in 3D FE models. In order to retain the main characteristic of random porous structure with controlled porosity, meso-structures of metal foams were constructed using Voronoi models, shown in Figure.2. The macro-scale dimension of both Voronoi specimen and solid specimen in simulation were set as diameter of 35 mm and length of 17.5 mm. There are about 1200 pores in the Voronoi model, which was constructed using the method as Yang (Yang2013) , with the average pore diameter of 3mm and porosity of 80%. For purpose of comparison, a solid specimen with the same size as Voronoi model was constructed. SHPB models were carried out according to real device to keep the characteristic of stress wave propagation in bars. The striker bar, incident bar and transmission bar included in SHPB were set as diameter of 37 mm, length of 1600 mm, 8000 mm and 4000 mm, respectively.

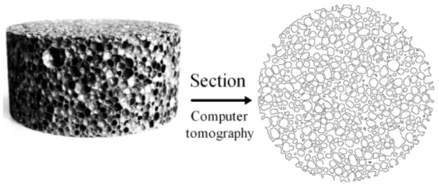


Figure.1 Section of Aluminum foams

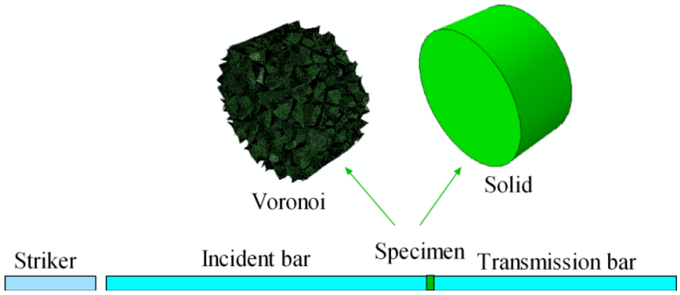


Figure.2 SHPB model and specimens model

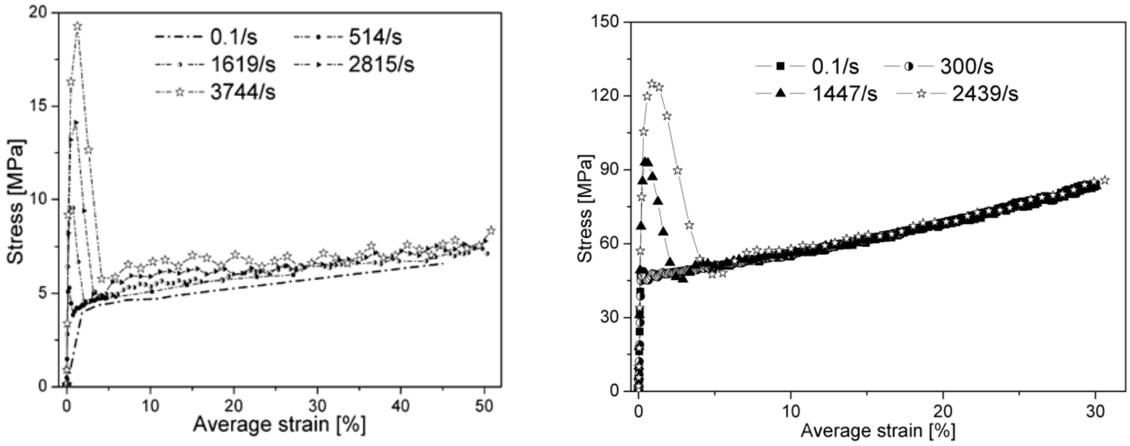
The FE analysis was perfomed on ABAQUS explicit. Figure. 2 shows the FE models for the whole testing system. The cell walls of Voronoi specimen were modeled using general-purpose shell element (S4R) with edge length less than 0.4 mm. Eight nodes solid element with edge length of 4 mm was used for the strike, incident bar and transmission bar. A general-contact interaction was set among the parts. In order to learn the mechanism of strain rate of the metal foam clearly, the material of cell walls is assumed to be no sensitive to the strain rate. Table 1 lists the mechancial properties of Voronoi foams and Hopkinson bars. The material is considerd as an elastic-plastic material with little hardening.

Table 1. Material properties in simulation

Material	Elastic modulus	Density [kg/m^3]	Poisson's ratio	Yield stress	Hardening modulus
Bulks (bars)	70 GPa	2.7e3	0.	-	
Cell walls (foams)	70 GPa	2.7e3	0.33	50MPa	40MPa

Results and discussion

Five different compressed speeds of specimens were carried out to study strain rate effect of metal foams. The impact speed of striker bar is from 10m/s to 70m/s, corresponding strain rate range 514/s to 3744/s in Voronoi specimen. When radial deformation overflowed the section of bars, the test results would be invalid. Hence, the impact speed of striker bar was restricted in a narrow range from 10m/s to 50m/s, corresponding strain rate range 300/s to 2439/s, on the solid specimen tests. Simulation results, as shown in Figure.3, indicated that there are some strain rate sensitivity occurred on Voronoi specimens and absence on solid specimens.

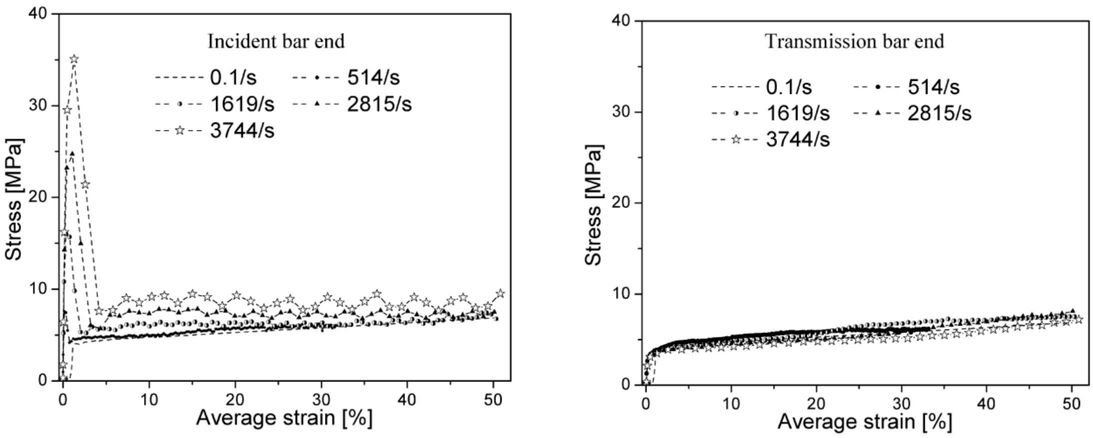


(a) Voronoi specimen (b) solid specimen

Figure.3 Stress-strain curve of specimens under different impact speed

Four factors as strain rate sensitivity of cell walls' material, micro inertia, air compressed pressure and localized deformation would affect the strain rate sensitivity of specimen. In these models, there is no strain rate sensitivity on matrix and no air compressed pressure. Hence, it just needs to consider the effect of inertia and localized deformation. With the observation of deformation of both Voronoi and solid specimens, it is found there are non-uniform deformation on Voronoi specimen, the concentration of strain occurred on one end or both ends and substantially uniform deformation on solid specimen. For the effect of inertia, there are some peaks on the initial stage of curves as shown Figure.3. The strain-stress curves of solid specimen aligned with each other after the peaks, while the curves of Voronoi specimen are different and still showed some strain rate sensitivity. For the existence of pores, localized deformation of Voronoi specimen is much different to that of solid specimen, which also led to different performance of strain rate sensitivity.

In this work, we can extract stress of bar ends directly and then analyzed the relationship between stress of bar ends and average strain of Voronoi specimen, as shown in Figure.4. The performance of strain rate sensitivity on the incident bar end is obvious, while that of transmission bar end is absence. For the obviously different performance of strain rate sensitivity on bar ends, the effect of inertia of cell wall and localized deformation on the ends of Voronoi specimens were further analyzed.



(a) Incident bar end (b) Transmission bar end

Figure.4 Stress-strain curves of Voronoi specimen

The performance of inertia which is resistance of changes specimen momentum or particle motion state, can be expressed as the acceleration of cell walls:

$$\sigma_a = \frac{F_a}{A_0} = \frac{\sum m_i a_i}{A_0} \tag{1}$$

where, m_i represents basic unit quality of Voronoi specimen, a_i represents corresponding axial acceleration, A_0 represents the initial area of specimen. Voronoi specimen was divided into eight equal parts to analyze the effect of inertia and localized deformation. The effect of inertia on the front part and the back part were assumed to represent the effect of inertia to incident bar end and transmission bar end, respectively.

Figure.5 shows the effect of inertia on both incident bar end and transmission bar end. The effect of inertia on incident bar end is great and that on transmission bar end can be neglect, which agree with the experimental observation by high-speed photography(Yang2013) : there is no obvious movement occurred in the transmission bar under first impact in SHPB tests.

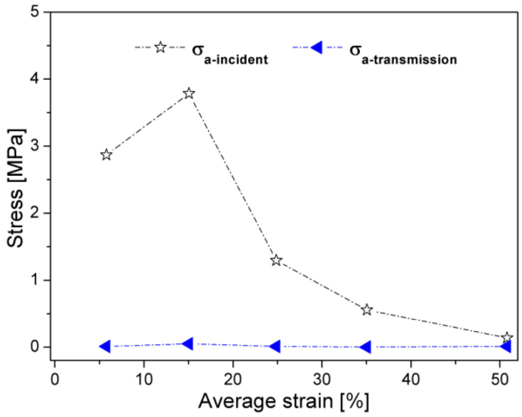
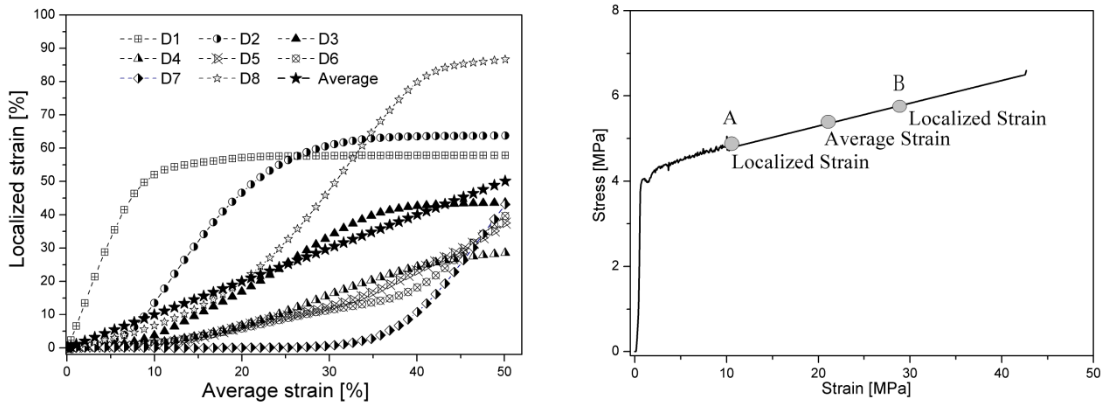


Figure.5 Effect of inertia on bar ends (3744/s)

The spatial distribution of strain of Voronoi specimen under impact is non-uniform, especially on the end of specimen, as shown in Figure.6 (a). Localized strain of the front end of specimen is always much greater than average strain of specimen under high -speed impact tests. While the localized strain of the back end of specimen is little lower than average strain at the first stage of curves (shown in Figure.6(a)) and become greater than average strain when average strain is more than 25%. With the increasing of impact speed, lower localized strain occurs on the back of specimen at the first stage of curves, which is consistent with the finding of Yang (Yang2013). Localized strain is much different from average strain of specimen, which may means that the stress is also non-uniform. Unfortunately, strain rate sensitivity was discussed only according to the relationship between stress and average strain of specimens. Figure.6(b) shows the stress-strain curve under quasi-static test (0.1/s). Under SHPB impact tests, when localized strain B is greater than average strain of specimen, corresponding stress B is greater, it will show "positive strain rate sensitivity", on the other hand, localized strain A is lower than average strain, it will show "negative strain rate sensitivity". This can explain some confusing relationship between stress and average strain, the stress under greater impact speed is little lower, under different impact speed test on the transmission bar end.



(a) (b)

Figure.6 Relationship between localized strain and average strain

To quantitatively analyze the performance of strain rate sensitivity, it can be described as the difference of stress corresponding to the same strain under different strain rates (set benchmark as quasi-static (0.1/s) result). Based on numerical simulation, the effect of inertia and localized deformation on the performance of strain rate sensitivity could be quantitatively measure. Table.1 illustrates the relationship between strain rate sensitivity and the effect of inertia and localized deformation on the ends of specimen under different strain rates. The quantitatively results shows that the performance of strain rate sensitivity is approximately equal to the sum of the effect of inertia and localized deformation. It means that effect of inertia and localized deformation are the primary cause of the strain rate sensitivity under the condition of cell wall material with no strain rate sensitivity.

Table.1 Relationship between strain rate sensitivity and effect of inertia and localized deformation

Imposed strain rate [s^{-1}]	Incident bar end							
	2815				3744			
Average strain [%]	5.4	15.6	25.3	35.8	5.8	15	24.8	35
Localized strain [%]	35.5	59.6	63.5	64.2	36.6	67.9	71.8	72.5
Effect of inertia [MPa]	1.1	0.2	0	0	2.9	1.3	0.3	0
Effect of localized deformation [MPa]	1.5	2.3	2	1.3	1.6	2.7	2.4	2
Performance of strain rate sensitivity [MPa]	2.6	2.8	1.9	1.2	4.4	4.1	3	1.8
Imposed strain rate [s^{-1}]	Transmission bar end							
	2815				3744			
Average strain [%]	5.4	15.6	25.3	35.8	5.8	15	24.8	35
Localized strain [%]	1	10.7	26	50	1.6	6.2	14.9	29.5
Effect of inertia [MPa]	-	-	-	-	-	-	-	-
Effect of localized deformation [MPa]	-0.5	-0.3	0	0.6	-0.5	-0.5	-0.5	-0.4
Performance of strain rate sensitivity [MPa]	-0.4	-0.2	-0.1	0.5	-0.5	-0.4	-0.6	-0.5

Conclusions

In the present paper, the FE model, using 3D Voronoi model simulated meso-structure of metal foams, was built to study the performance of strain rate sensitivity under different impact speeds (or strain rates). The numerical results indicated that metal foams show some strain rate sensitivity even under the condition of cell walls' material with no strain rate sensitivity, which was attributed to the effect of inertia and localized deformation. The performance of strain rate sensitivity on incident bar end and that on transmission bar end are very different: obvious strain rate sensitivity on incident bar end and absence of strain rate sensitivity on transmission bar end. Therefore, different data processing method during SHPB tests may be a cause of controversy on the existing literature.

Acknowledgements

This work was financially supported by the National Natural Science Foundation of China (Grant No. 90916026, 11202081, 11272124) and State Key Laboratory of Subtropical Building Science (2012ZC24).

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