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Effect of retained porosity due to additive manufacturing on dynamic loadings

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Abstract. The major advantage of additive manufacturing (AM) of metallic materials is the capacity to produce parts with complex geometry that are difficult to achieve with conventional processes. However, for applications subjected to high-strain rate loadings, improving the understanding of the dynamic behavior of AM high strenght steel is essential to enlarge the range of application for such AM metals. Experiments have shown that even if for quasi-static and moderate strain-rates (of the order of 10^2-10^3/s), the mechanical response of additively manufactured (AM) and traditionally processed materials is similar, the impact behavior is markedly different. In this paper, we reveal that the main reason for this difference is the retained porosity in the AM material. To gain understanding, a numerical study using an elastic/plastic damage model that accounts for the effects of the tension-compression asymmetry in plastic deformation and its influence on porosity evolution is performed for material with different level of retained porosity. The finite-element results reveal that even a very small amount of initial porosity leads to an increase in the shock rise time, explaining the observed trends.

Introduction

Flyer-plate impact testing (e.g. [1], [2]) allows investigating the mechanical behavior of materials under very high strain-rates and high stress conditions (e.g. strain-rate of the order of 10^4-10^6/s for metallic materials). The plates are designed such as to ensure that the material at the center of both plates is inertially confined for a sufficient time, so that nearly one-dimensional strain conditions are achieved. The experiment involves an impactor plate (or flyer plate) which is launched against the target plate, which is initially at rest. Generally, the impactor and target plate are made of the same material. When the impactor plate (or flyer plate) impacts the target plate, which is initially at rest, an elastic compressive wave is generated at the impact interface and travels in both plates and reflects off at interfaces and free surfaces as tensile waves. The thickness of the impactor and target are taken such as to ensure that the reflected waves (tensile rarefactions) would meet near the center of the specimen and produce spall fracture.

High-strength martensitic steels are a valuable class of structural materials due to their exceptional combination of strength, toughness, and affordability. Metal additive manufacturing of high strength steel is becoming an efficient technology for production of geometrically complex parts. However, while it has been recently demonstrated that martensitic steel can be successfully produced using laser powder bed fusion, the AM process material retain a very small porosity (see [3]). However, for a range of potential new applications of AM high strength steels materials, understanding the mechanical response of AM material under very high strain-rate is essential and largely remain unexplored.

Very recently, experiments on AM high strength steel have shown that even if for quasi-static and moderate strain-rates (of the order of 10^2-10^3/s), the mechanical response of additively manufactured (AM) and traditionally processed materials is similar, the impact behavior is markedly different (see plate impact experiments on wrought high strength steel [4] and AM high strength steel [5]). Furthermore, Revil-Baudard et al. [5] have put into evidence the role of the retained porosity on the shock structure occurring inside such AM high strength steels materials. Furthermore, the authors shows that they were able to describe with a unique constitutive model the behavior of both wrought and AM high strength steels material subjected to flyer-plate impact. The FE predictions were found to be in good agreement with the test results for both type of materials. Both elastic precursor and weak shock wave structures were accurately predicted including time of arrival magnitudes.

In this work, we hypothesize that even though the retained porosity in these AM high-strength steels is very small, it may have a distinct influence on the shock response, in particular on the velocity profile up to the Hugoniot state. Fully-implicit finite element calculations are presented in which we simulate both the launching of the impact plate and the impact between the two plates. The constitutive model used is the Cazacu and Stewart potential [6] for porous materials with matrix displaying tension-compression asymmetry and Johnson-Cook [7] hardening law that accounts for both strain-rate effects and plastic history. The plate impact FE simulations are conducted for various initial porosities in the range 0 to 2% with identical model parameters and elastic properties and an impact velocity of 400m/s.

Constitutive model

It is well recognized that due to their BCT structure, high strength martensitic steels display a different plastic response under monotonic uniaxial tension and compression although no volume changes accompany yielding (e.g. see [5], [8]). To model simultaneously the effects of the tension-compression asymmetry in the plastic deformation of martensitic steels and the influence of the retained porosity due to the additive manufacturing process, the potential for isotropic porous metals developed by Cazacu and Stewart [6] is used (Eq. 1), namely:

$$\varphi(\sigma, f) = m^2 \sum_{i=1}^{3} \left(\frac{|\sigma_i'| - k\sigma_i'}{\bar{\sigma}}\right)^2 + 2f \cosh\left(z_s \frac{3\sigma_m}{2\bar{\sigma}}\right) - (1 + f^2), \tag{1}$$

where f denotes the porosity, k is a parameter that describes the tension-compression asymmetry in plastic deformation, $\sigma_1', \sigma_2', \sigma_3'$ are the principal values of the stress deviator $\boldsymbol{\sigma'}$ and σ_m is the mean stress. Specifically, the parameter k can be expressed solely in terms of the ratio between the yield stresses in uniaxial tension and compression while all the remaining parameters involved in the Cazacu and Stewart potential are expressed in terms of the parameter k (Eqs. 2 and 3), i.e.:

$$m = \sqrt{\frac{9}{2(3k^2 - 2k + 3)}}; \tag{2}$$

$$z_s = \begin{cases} 1 & \text{if} \quad \sigma_m \geq 0, \\ \sqrt{\frac{3k^2 + 2k + 3}{3k^2 - 2k + 3}} & \text{if} \quad \sigma_m < 0. \end{cases} \tag{3}$$

In the absence of porosity, the Cazacu and Stewart yield criterion recover the isotropic form of the Cazacu et al. [9] plastic potential for fully-dense metallic materials. It is also worth noting that if the matrix (void-free material) has the same response in tension and compression, the Gurson

[10] potential is recovered. The total rate of deformation D is the sum of an elastic part and a plastic part D^p. The elastic response (Eq. 4) is described as:

$$\dot{\sigma} = C^e : (D - D^p), \tag{4}$$

where $\dot{\sigma}$ is the objective rate of the Cauchy stress tensor σ, C^e is the fourth-order elastic stiffness tensor. The plastic strain rate D^p is obtained assuming associated flow rule (Eq. 5) as:

$$D^p = \dot{\lambda}\frac{\partial \phi}{\partial \sigma}, \tag{5}$$

where $\dot{\lambda}$ is the plastic multiplier. Hardening is considered to be governed by a Johnson-Cook type law (Eq. 6) such as to describe both strain-rate effects and the history of plastic deformation [7], i.e.:

$$\bar{\sigma} = (A + B(\bar{\varepsilon}^p)^n)\left(1 + C\, ln\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right), \tag{6}$$

where $\dot{\bar{\varepsilon}}$ denotes the strain-rate and $\bar{\varepsilon}^p$ is the equivalent plastic strain while *A*, *B*, *C*, the exponent *n* , and the reference strain-rate $\dot{\bar{\varepsilon}}_0$ are constants. The evolution of the porosity is given by Eq. 7:

$$\dot{f} = (1 - f)\frac{\partial \varphi}{\partial \sigma_m}. \tag{7}$$

For more details about the constitutive model and its implementation into a F.E. software, the reader is referred to the books of Cazacu et al. [11] and Cazacu and Revil-Baudard [12].

Plate impact predictions for AM materials

FE simulations of plate impact test were performed using the constitutive model described in the previous section in conjunction with the dynamic implicit solver in Abaqus Standard. A simplified FE setup is considered for the simulation under the assumption that the edge effects are negligible on the evolution of the velocity of the back surface of the center specimen. The simulations were performed in two phases, associated to the launching of the impact plate, and the impact between the two plates, respectively. In the first phase, the impact velocity was applied to all the nodes belonging to the impact plate such as to represent the launch of the impact plate. In the second phase, i.e. the impact phase, all the prescribed velocity conditions are removed (i.e. only inertia is driving the impact problem). In this manner, the experimental conditions are reproduced with fidelity. The thickness of the impact plate is of 1.6 mm while the target plate thickness is 3 mm. The elastic parameters values used in all simulations are E = 210 GPa, ν = 0.3, where E is the Young modulus and ν is the Poisson coefficient. The tension-compression parameters of the Cazacu and Stewart criterion is set to k = – 0.41 and the parameters of the Johnson Cook hardening law are A = 905.0 MPa, B = 1501.8 MPa, C = 1.28 10^{-3}, n = 0.212 and $\dot{\epsilon}_0$= 0.001, which are typical values for a high strength martensitic steel. The density value was ρ =7800 kg/m^3.

In this work, we present a detailed analysis for an impact velocity, v = 400 m/s. To study how the presence of even a small amount of retained porosity affects the mechanical response of high strength steels under impact conditions, F.E. simulations of the plate impact tests according to the Cazacu and Stewart model in conjunction with the Johnson-Cook hardening law are investigated for several levels of retained porosity f_0 = 0, 0.0001, 0.0005, 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009, 0.01, 0.02.

The predicted isocontours of the axial velocity at a time t = 0.5 μs after impact for the wrought material (f_0 = 0) and the AM high strength steel for several level of initial porosity (f_0 = 0.001, 0.006 and 0.0125) is shown in Fig. 1. The wave propagation speed is clearly influenced by the level of retained porosity due to the AM processing. The larger is the retained porosity, the slower is the propagation of the wave inside the specimen.

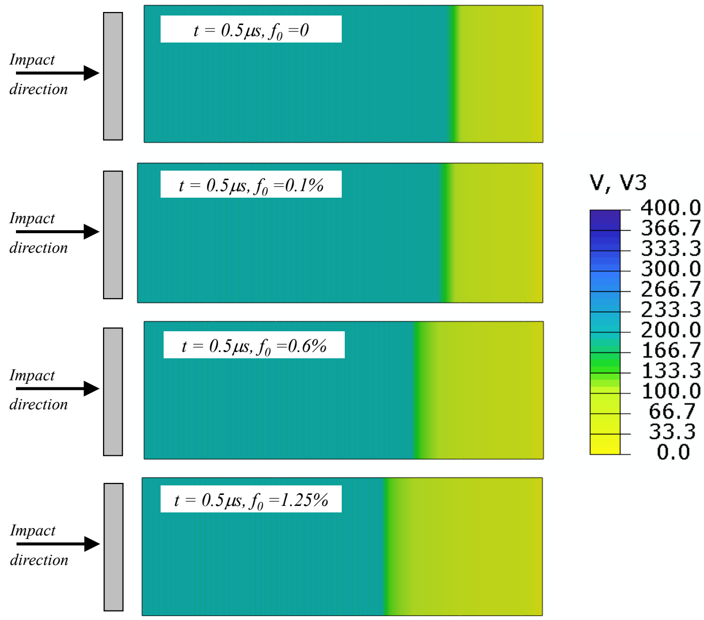

Figure 1 – F.E. isocontours of axial velocity at a time t=0.5 ms after impact for specimen with different level of retained porosity ranging from 0 to 1.25% (top to bottom). Impact velocity of 400 m/s.

While the influence of the initial level of porosity is clearly seen on the plastic wave speed, the influence of the initial level of porosity on the shock profile, that is measured as the axial velocity of the back surface. The time-evolution of the axial velocity of the rear surface of the target plate for the high strength steel for several level of porosity is plotted in Fig. 2. The Hugoniot Elastic Limit (HEL) represents the maximum stress that a solid material can sustain under one-dimensional shock compression loading that does not irreversibly change the material, i.e. under the HEL limit only elastic deformation will occur in the specimen. In the time evolution of the back surface velocity of the specimen, the HEL is located at the end of the 1st ramp of the velocity, i.e. when the time evolution of the velocity is no more linear (see Fig. 2). Note that greater initial porosity slightly decreases the HEL.

The back surface velocity also exhibits a sigmoidal rise from the HEL to a plateau called the Hugoniot state, or Hugoniot plateau. During this sigmoidal rise, plastic deformation occurs in the specimen. The height of the Hugoniot state provides information on the shock loading experienced by the specimen. After the HEL, the influence of the retained porosity on the shock profile becomes important: the rise time, i.e. the time needed to reach the Hugoniot state becomes longer as the retained porosity increases. In other words, the slope of the time evolution of the axial velocity between the HEL and the Hugoniot state is lower as the initial porosity increases. Moreover, as the initial level of retained porosity changes the level of the Hugoniot plateau, this plateau being reach for lower velocity when the initial porosity increases.

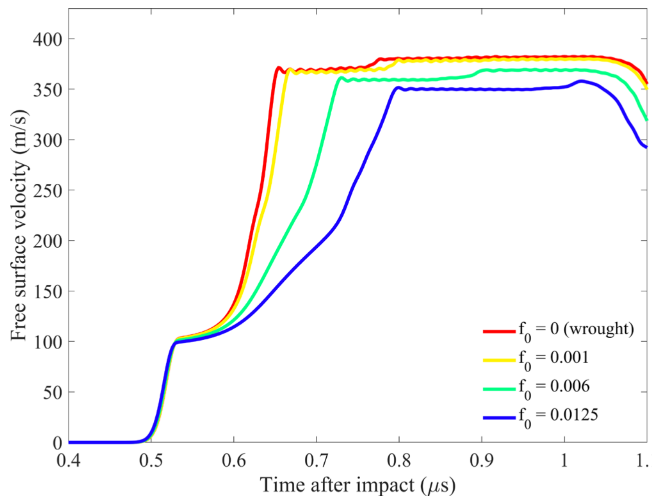

Figure 2 – F.E. predictions of the target rear free surface velocity for different values of the initial porosity, f_0. Impact velocity of 400 m/s.

To further investigate the influence of the initial porosity on the shock structure, for each initial porosity, the shock velocity U_S is determined as the ratio between the target thickness and the arrival time of the shock wave. The arrival time of the shock wave is determined as the time at which the axial velocity has reached the Hugoniot plateau. The variation of the shock velocity U_S with the initial porosity is plotted in Fig. 3. Since a larger retained porosity delay the time at which the Hugoniot state is reached, the shock velocity decreases as the initial porosity increase. Furthermore, it is predicted that the variation of the shock velocity U_S decreases almost linearly with the initial porosity.

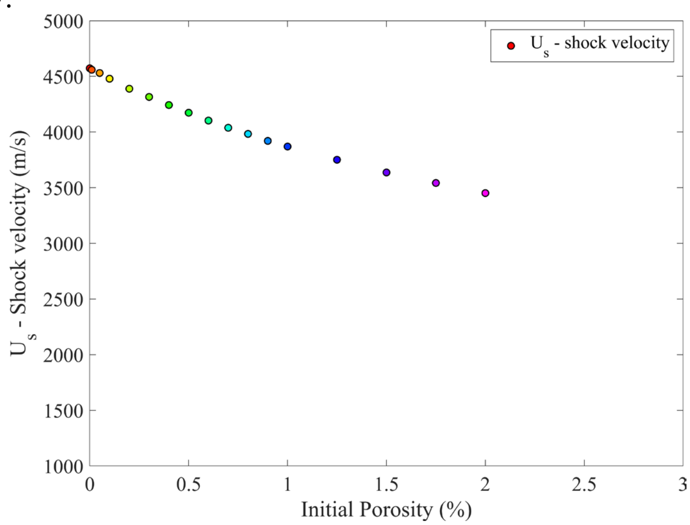

Figure 3 – Shock rise time (diamonds) and shock velocity (circles) extracted from F.E. simulations as a function of initial material porosity $\boldsymbol{f_0}$ (%). Impact velocity of 400 m/s.

It is also worthwhile analyzing how the level of the initial retained porosity influences the level of equivalent plastic strain experienced by the target plate. The time evolution of the equivalent plastic strain associated to the Cazacu and Stewart porous criterion for several level of initial porosity f_0 is plotted in Fig. 4. It is clearly seen as the initial level of retained porosity increases, the time needed to reach the Hugoniot plateau increases, meaning that the plastic front wave is spamming over a larger distance for larger level of retained porosity. Furthermore, the level of the equivalent plastic strain at the Hugoniot plateau increase as the initial porosity increases.

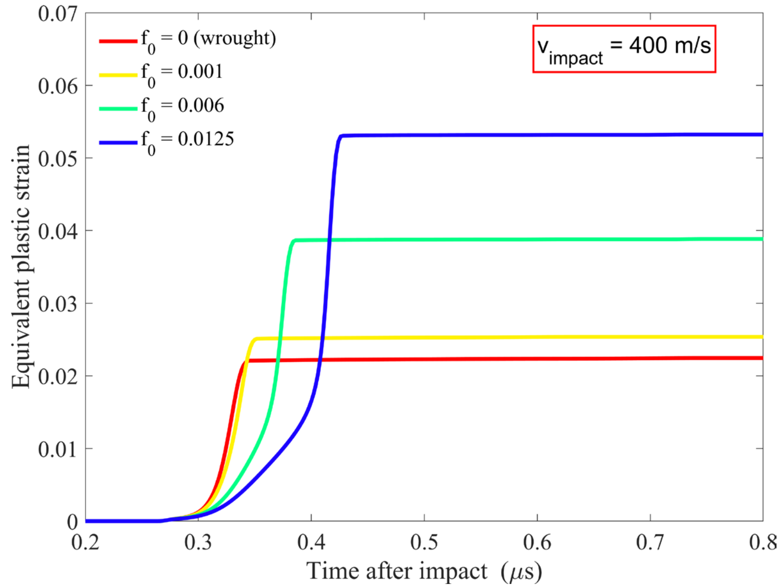

Figure 4 – F.E. predictions for the time evolution of the compressive axial plastic strain at a location 1.5 mm from the impact surface for several values of initial porosity. Impact velocity of 400 m/s.

Conclusions

In this work, the influence of the presence of even a small amount of retained porosity due to the additive manufacturing process on the mechanical response of high-strength steels under impact conditions has been investigated by numerical means. To this end, FE simulations were conducted for an initial porosity, f_0, in the range f_0 = 0 to f_0 = 2 % using the elastic/plastic model of Cazacu and Stewart (2009) for porous ductile materials with matrix displaying tension-compression asymmetry and Johnson-Cook hardening law that accounts for both strain-rate effects and plastic history. The FE predictions indicated that the plastic wave speed is slower and more diffuse when the level of initial porosity is higher. Notably, it was predicted that even a very small initial porosity decreases the Hugoniot while increasing the shock rise time. This change in rise time was caused by a consistent reduction in the slope of velocity, delaying the onset of the Hugoniot. Moreover, it was shown reduction in the final Hugoniot state when compared to a void free material.

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