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Dynamic response of Hastelloy® X plates under oblique shocks: Experimental and numerical studies

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ABSTRACT

The dynamic behavior of Hastelloy® X plates subjected to normal and oblique shock loading was studied both experimentally and numerically. A series of experiments was conducted on Hastelloy® X plates at room temperature under fixed boundary conditions using a shock tube apparatus. High-speed digital cameras were used to obtain the real-time images of the specimen during the shock loading. Digital image correlation (DIC) technique was utilized to obtain 3D deformations of the plates using stereo-images of the specimen. The numerical modeling utilized the finite element software package Dynamic System Mechanics Analysis Simulation (DYSMAS), which includes both the structural analysis as well as the fluid–structure interaction to study the dynamic behavior of the specimen under given loads. Experimentally obtained pressure–time profiles were used as a reference in numerical modeling. It was observed that the lower angles of shock incidence caused more deformation on the specimen. Additionally for oblique shocked specimens, the deformation was observed to initiate from the edge nearer to the muzzle. The results from the numerical simulations were validated with the experimental data, and showed excellent correlation for all cases.

1. Introduction

An experimental and numerical study was conducted to understand deformation in a superalloy Hastelloy® X when subjected to normal and oblique strong shock wave loadings. The experiments incorporated real-time diagnostics to understand the structural behavior of Hastelloy® X plates. The numerical simulations included fluid–structure interactions in the dynamic analysis of the problem.

The study is motivated by the need to understand response of aerospace structures to highly dynamic strong shock loadings at various angles of incidence. There are few materials that come close to fulfilling the stringent requirements placed on aerospace structures that operate under extreme conditions of loadings. These extreme conditions include highly dynamic loads, extreme temperatures and pressures and other environments. One class of materials that have shown promise for such applications are nickel based superalloys including Hastelloy® X. This material shows high oxidation resistance, machinability, and has the capability of retaining its strength to a greater extent at high temperatures [1,2].

Many researchers have studied, both experimentally and numerically, the behavior of monolithic plates subjected to shock loading. The classic experimental work of Menkes and Opat [3] on the clamped aluminum beams subjected to shock loading identified three damage modes namely mode-I (inelastic deformation), mode-II (tearing at the extreme fiber) and mode-III (transverse shear at the support). The subsequent experimental studies of Teeling-Smith and Nurick [4], Nurick and Shave [5], Olson et al. [6] and Shen and Jones [7] reported the same kind of failure modes when a structure is subjected to blast loading. The experimental and numerical investigation of Nurick et al. [8], Chung Kim Yuen and Nurick [9] and Langdon et al. [10] shed some light on the effect of stiffeners and their configuration on the blast loading of stiffened plates. Balden and Nurick [11] performed the numerical simulations to differentiate the deformation, post-failure response of uniform and localized blast loaded plates. In recent years, many researchers used numerical methods to understand this complex problem [12–16]. Very recently, Abotula et al. [17] conducted a series of experiments to investigate the response of simply supported Hastelloy® X plates subjected to shock loading at temperatures up to 900 °C. They found that the maximum deflection of the plate increased with the temperature and was 160% higher at 900 °C when compared to that at room temperature. All these studies focused on normally incident shock loadings on the structures. Gray et al. [18] have used direct detonation-wave shock loading on metallic plates. They have found increased shock hardening and twin formation with increasing shock

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Table 1
Nominal chemical composition, weight percentage [1].

Ni	Cr	Fe	Mo	Co	W	C	Mn	Si	B
47[a]	22	18	9	1.5	0.6	0.1	1*	1*	0.008*

[a] As balance.
* Maximum.

obliquity. Aerospace structures are often subjected to long duration oblique shocks that last a few milliseconds and thus, there is need to understand the response of aerospace materials under these loads.

The experiments in this study utilized 3D DIC technique coupled with high speed photography to measure the out-of-plane deflections of the specimen for 0°, 15° and 30° incident angles. The investigation was further extended using DYSMAS to study the response for 45° and 60° incident angles. Experimental results are utilized to validate the numerical model. The results manifest more deformation at lower angles of incidence. In case of oblique shocked specimens, the deformation initiates from the edge closer to the shock tube muzzle. The peak out-of-plane deflection is observed to vary nonlinearly.

2. Experimental procedure

A series of experiments was carried out to study the dynamic deformation of plates subjected to normal and oblique shocks.

Table 2
Typical physical properties [1].

Density	8220 Kg/m^3
Melting range	1260–1355 °C
Elastic modulus	205 GPa (at 25 °C)
Yield stress	380 MPa (at 25 °C)

Table 3
Hastelloy® X Johnson–Cook parameters [2].

A	B	C	n	m	$\dot{\varepsilon}_0$
380 MPa	1200 MPa	0.012	0.55	2.5	0.01 s^{-1}

Hastelloy® X was selected as a material of choice for the experiments due to its exceptional performance compared to typical structural steels.

2.1. Material, specimen geometry and boundary conditions

Hastelloy® X is a nickel based superalloy with high oxidation resistance, good machinability and high-temperature strength. Table 1 provides the chemical composition of the material. The presence of a high percentage of Ni imparts good strength even at elevated temperatures. Chromium is responsible for the high oxidation resistance. Typical physical properties of this material are given in Table 2. The dynamic constitutive behavior of Hastelloy® X was recently investigated [2] and the Johnson–Cook (J–C) parameters were reported as shown in Table 3. This J–C plasticity model was used in the numerical investigation. The Johnson–Cook (J–C) plasticity model incorporates Mises plasticity criteria with analytical forms of the hardening law and rate dependence. J–C model has been found suitable for computations of high-strain-rate deformation of most metals.

The monolithic Hastelloy® X plates used in this study have a length of 203 mm, width of 51 mm and thickness of 3 mm. Since the main objective of this study is to investigate the response of monolithic Hastelloy® X plates subjected to oblique shocks, a clamped boundary condition was used at the top and bottom of the specimen. The vertical edges of the specimen were unsupported. The details of specimen and boundary conditions can be seen in Fig. 1a. The unsupported length of specimen was 152 mm.

2.2. Experimental arrangement

Experiments were conducted to understand the behavior of Hastelloy® X plates subjected to shock wave with an angle of incidence (angle between the incident shock front and the reflecting surface) of 0° (normal shock), 15° and 30°. These incident angles were obtained by deflecting the specimens at angles 90°, 75° and 60°, respectively, with shock tube axis. For each shock incident angle, three experiments were conducted to ensure repeatability of the results. The schematic top-view of the experimental setup with different angles of incidence is shown in Fig. 1b.

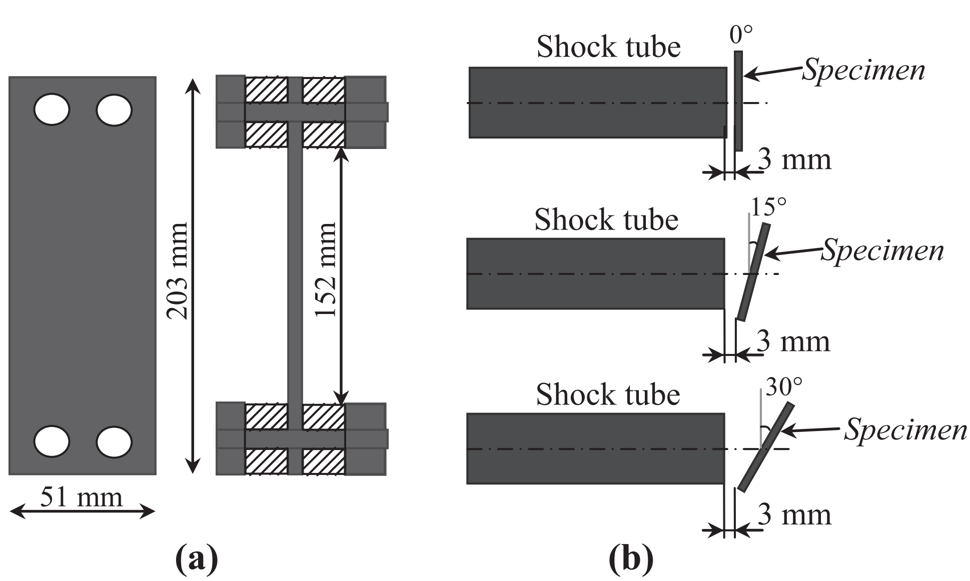

Fig. 1. (a) Specimen dimensions and boundary conditions (b) Schematic top-view of setup for different incident angles.