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Reverse ballistic experiment resembling the conditions in turbine blade off event for containment structures

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ABSTRACT

An experimental technique has been developed which allows loading of heated sheet material under impact conditions with simultaneous measurement of the impact force history. The combined characteristics of impact loading at elevated temperature makes the experiment ideal for validation of models used to simulate the containment structure surrounding aircraft engines. In this paper experimental results for Alloy 718 are presented, a nickel based super alloy commonly used in hot parts of the containment structure. The experimental results are then compared to simulations in order to validate previously calibrated material parameters. The basic principle of the validation experiment is based on reverse ballistics, in which a thin circular specimen with free boundaries impacts the end of an instrumented rod. Using induction heating the specimen is heated to temperatures up to 650 °C and a gun driven by compressed air accelerates the specimens to desired velocity. In the reported work velocities are kept low enough to avoid cracking and thus the study is limited to plastic conditions, even though the technique is applicable also for fracture studies. The free boundaries of the experiment makes numerical modelling and simulation straightforward, making it valuable as a validation tool. All numerical simulations are performed using the commercial finite element code LS-Dyna and plastic behaviour of the material was modelled with the Johnson-Cook material model.

1. Introduction

Time dependent deformation of materials is an extensive research field ranging from creep, with a timescale of years, to impact, often with a typical timescale of a few hundred microseconds. The response of a material when subjected to rapidly changing loads can differ drastically from when it is subjected to static or quasi-static loading. At low loading rates an impacted object will react on a global scale under elastic and plastic deformations transporting large parts of the impact energy away from the contact area while dissipating parts of the energy. At higher impact velocities the energy does not have time to dissipate whereby local response will dominate. In some cases the locally applied energy will be large enough to rupture the material, making an otherwise ductile material behave in a brittle manner at high loading rates. This complex situation means that good understanding of a material's dynamic response across a wide range of strain rates is very important in order to be able to predict the outcome of an impact. Meyers [1] gives a good overview of the subject of dynamic behaviour of materials, from elastic and plastic loading of quasi-static character to high strain rate impact.

The complex nature of dynamic material behaviour has meant that extensive experimental testing has always been an essential part when designing the containment structure in aeroengines. Full scale engine containment testing are complex, time consuming, and expensive. Breaking down the containment tests into smaller component experiments, such as the testing performed by Xuan and Wu [2], can save both time and resources. In resent years the increasing power of computers has led to continued development of more powerful simulation models. This has enabled numerical testing of complex containment cases, such as the effects of multiple blade interaction performed by He et al. [3]. However extensive simulations with high demands on reliability require very accurate modelling of material behaviour. Field et al. [4] has written a review of the most commonly used experiments for calibration of material models at high strain rate, such as Taylor impact, Hopkinson bar, Drop weight and Ballistic impact. These tests cover a strain rate regime of many magnitudes, typically strain rates from 10^2 to $10^5\ s^{-1}$ can be achieved.

The aim of the work presented here is to design and build a high strain rate experiment that shows the dynamic behaviour of material at multiple temperatures. At the same time the experiment should be straightforward to model numerically in order for it to be used as a validation tool. Numerous experiments have been designed to be used as validation tools. For example Dey et al. [5]

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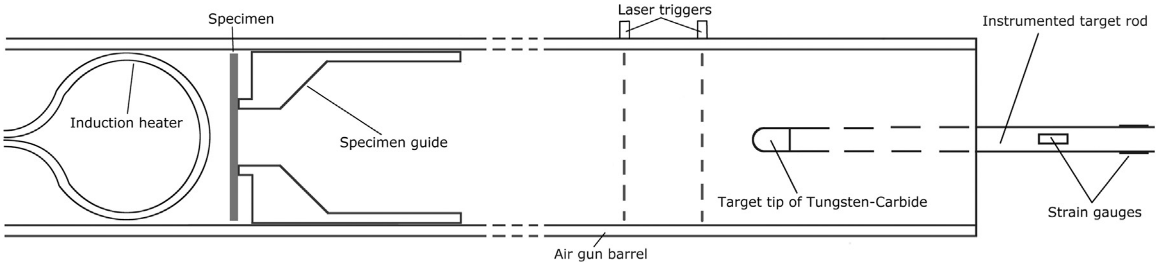

Fig. 1. Schematic of the experimental set up.

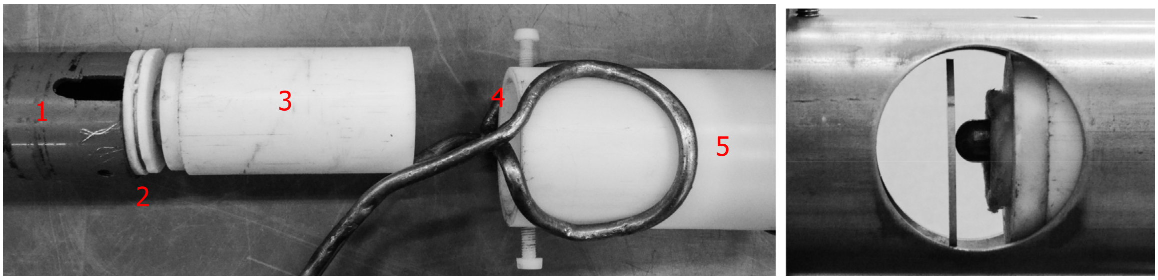

Fig. 2. Pictures on the two ends of the gun barrel. The leftmost picture shows the back end before loading the cannon. The picture to the right show the specimen separated from the specimen guide as it touches the tip of the target rod.

Table 1
Parameters for the Johnson-Cook model.

A [MPa]	B [MPa]	n [–]	C [–]	m [–]	$\dot{\varepsilon}_0^p$ [–]	T_m [K]	T_0 [K]
1176	1456	0.5307	3.54E^{-3}	1.740	0.002	1573	293

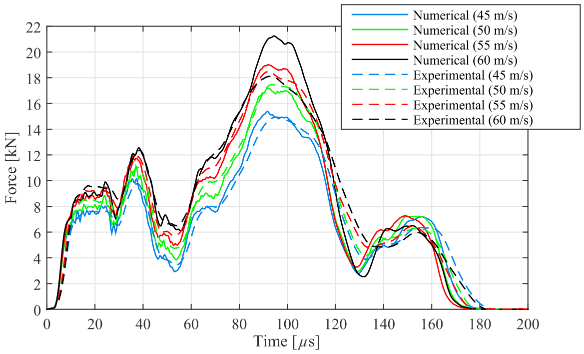

Fig. 3. Comparison between averaged experimental (dashed lines) and numerical results (solid lines) at room temperature performed at four different velocities.

used an impact experiment to evaluate the ballistic limit of double layered armour compared to single layered, comparing the experimental results with numerical simulations. Børvik et al. [6] used an impact experiment to evaluate the ability of a fully coupled material model of viscoplasticity and ductile damage to predict the behaviour of metal sheets penetrated by blunt projectiles. In the current investigation a method based on so called reverse ballistics was chosen. The principle of the experiment is accelerating a heated specimen using an air gun towards a target. The target is in this case an instrumented rod able to register the force during the impact. Similar approaches have been used by for example Bourne et al. [7] and Proud et al. [8] to observe penetration behaviour of metals at oblique impact at a velocity of approximately 700 m/s. Hockauf et al. [9] used a reverse impact experiment to test dynamic perforation of fibre fabrics and polymers at impact velocities of 230 m/s. In the present case thin metallic sheet material is investigated and therefore significantly lower impact speeds are used. The designed experiment resembles the set-up used by Liutkus [10], who used reverse impact in a dynamic punch test coupled with digital image correlation equipment in order to test the plastic deformation of Alloy 718. One major difference is that the experimental set-up proposed in this paper is designed to ensure that the specimen is free from boundary effects and thereby very straightforward to model.

The experiment is here used to validate material parameters used to model the plastic behaviour of a batch of Alloy 718 supplied in aged condition. The ability of Alloy 718 to retain most of its strength at temperatures up to 650 °C, coupled with its exceptional corrosion resistance and high weldability makes it one of the most extensively used materials in containment structures and other load carrying parts in hot sections of aircraft engines. The conditions which the containment structure has to be able to withstand include combined effects of high strain rate and elevated temperatures, making the designed validation experiment advantageous.

2. Experimental

The basic principle of the experiment is shown in Fig. 1. An air gun with a 5 m long barrel having an inner diameter of 50.8 mm is used to accelerate the projectile to desired velocity. Pressures of 100–160 kPa, giving impact velocities between 40 and 60 m/s, were used in order to find the highest velocity at which no visible fracture occurs while at the same time obtaining maximal plastic deformation. To measure the velocity of the specimen two laser operated photocells are placed in the gun barrel just ahead of the target. At this position openings in the side of the barrel release the driving pressure behind the projectile so that an approximately constant velocity was achieved just before impact. In order to ensure that the impact was correctly aligned and as concentric as possible the specimen guide was still supported in the gun barrel when the specimen impacted the target.

More details can be seen in the two photos in Fig. 2. The photo to the left show the rear end of the cannon barrel. The part marked as (1) is the pipe going to the air tank filled with compressed air. Next to this is the thin specimen put in between two sheets of