Materials and Design 64 (2014) 650–659

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Dynamic behaviour of high strength steel parts developed through laser assisted direct metal deposition

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ARTICLE INFO

Article history:
Received 5 May 2014
Accepted 8 August 2014
Available online 19 August 2014

Keywords:
Dynamic behaviour
High strain rate
Direct metal deposition
High strength steels

ABSTRACT

High strength steel alloys are good candidates for many engineering applications particularly those involving high strains and impact loads. Such applications in energy absorption devices require materials that can sustain dynamic loading and remain strong under demanding conditions. But the processing cost of these alloys has been a prohibitive factor, thus re-enforcing the research on porous and cellular structures made of stainless steels. Direct metal deposition (DMD) is a process which employs the power of a CO_2 laser to melt and deposit metallic powders onto steel substrates. Such structures offer advantages of creating novel configurations only by computer control of laser "tool path". This research investigates the mechanical behaviour of solid and porous parts with prismatic cavities under quasi-static and dynamic compressive loading. Apart from two main deficiencies of relatively large variations of properties among the test specimen and sufficiently low modulus of elasticity, the stress strain behaviour is very close to the commercial grades of stainless steel produced by rolling and forming. The energy absorption behaviour of porous specimen is also very encouraging and renders DMD as a suitable process for manufacturing of customized sandwich and graded structures that can be used as a substitution for many engineering applications such as monolithic compression plates and explosion shields.

1. Introduction

During the last 15 years, rapid prototyping and laser assisted additive manufacturing (LAAM) techniques for producing metallic parts and components have been revolutionizing and simultaneously challenging the conventional manufacturing strategies and applications [1]. Due to several constraints, these technologies cannot be regarded as comparable to manufacturing techniques like forming, rolling, die casting and forging at mass production level; but at customized and low volume production level these technologies offer distinct advantages of creating intricate shapes without tooling and with better control over material properties augmented by the availability of wide range of materials-to-process in powder form. Laser assisted direct metal deposition (DMD) possesses very good capability to work on high strength and tough austenitic stainless steels, H13 tool steel and biocompatible metals like titanium alloys and tantalum [2]. DMD provides the facility to produce complex geometrical features and functionally graded structures through Computer Aided Design (CAD) control. In a closed-loop DMD system a whole new class of optimally designed materials can be produced by depositing multiple materials at different parts of a single component with high precision [3]. It also provides the unique opportunity to manufacture large size parts that can be used as prototypes in numerous applications owing to its large bed size of 2 m × 1 m area [4]. These parts can be used in applications such as highly stressed machine components, plates under large compressive loads and barriers for restricting impact and shock loads due to physical projectiles or explosive forces.

The parts developed on DMD are actually made in a manner that involves creation of material and part simultaneously. Parts with complete shape and form are generated as a result of sintering of powdered material and subsequent layer by layer deposition over a "compatible" substrate through the assistance of high power and highly focussed laser beam. Unlike powder metallurgy, there are no compacting forces involved and there are process associated heat transfers which can result in generation of residual stresses and non-uniformities like micro-porosity and non-homogenous microstructures, irrespective of the materials cladded. Thus the most essential need for any laser generated part is to ensure the character of structures generated and the consistency of mechanical properties vital for employment in engineering applications like those mentioned above [5,6].

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http://dx.doi.org/10.1016/j.matdes.2014.08.026
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For the last two decades porous and cellular metallic structures and their special sub-class called "metallic foams" [7–9] are enjoying a sustainable development curve while finding numerous applications in engineering and medicine, some of which include lightweight and stiff structures, energy absorption devices at predictable and uniform stress level and biomedical scaffolds and implants [10,11]. High strength stainless steel alloys in the form of sandwiched structures are considered a powerful candidate for bearing impact loads without fracture and efficiently absorbing the energy of explosions and blasts [12]. Rathbun et al. [13] tested the dynamic performance of solid and sandwiched beams made from 304 SS under impact velocities of 140–470 m/s. Their results, later supported by the investigations of Radford et al. [14], concluded that wherever the loading is dominated by bending instead of stretching like impulses representative of those expected from nearby shocks, the metallic sandwich structures outperform monolithic solids of equivalent weight. And the best core topologies that provide simultaneous crushing and stretching resistance include square honeycombs.

High strength stainless steel alloys demonstrate some peculiar characteristics that forbid a straightforward transition towards ascertaining their design performance based on the characteristics and behaviour of carbon steels. The noticeable deviating instances are non-linear stress strain relationship in the elastic region, no sharply defined yield point and substantial strain hardening in the plastic region of deformation [15]. That's why the ensuing research on stainless steel alloys encompasses every possible investigation aspect which includes numerical modelling, finite element prediction and formulation of constitutive stress strain relationships [16].

The objective of this paper is to investigate the mechanical properties of DMD generated high strength steel alloy parts and ascertain their characteristics in the yielding zone through quasi static testing and under high strain rate compressive loading using a Split Hopkinson Pressure Bar (SHPB) apparatus. This effort provides a useful insight into the quality of DMD generated specimen and also helps in diagnosing the abnormalities in their stress strain relationship which is expected for a novel method of production. The materials investigated are 316L stainless steel (SS) and H13 tool steel (TS). Mechanical properties of austenitic stainless steels from commercially available grades 304 and 316L have been investigated by many researchers covering diversified applications [17,18]. But there is a significant gap in the research on properties of these materials developed by laser cladding. Mechanical properties under focus are stress strain behaviour over elastic and plastic regions and determination of yield strengths and moduli of elasticity. Another important aspect of this investigation is the comparison of fully solid parts with those having cavities or macro-pores. Reason for this approach is that if porous parts developed on DMD prove themselves to be amply strong and tough particularly under impact loads then a whole new vista of opportunities for developing honeycombs and sandwiched structures of customized shapes and configurations will be opened. The research extends the investigation into mathematical modelling of deformation characteristics of laser generated parts in the light of established models already derived for commercially available stainless steels. Subsequent comparison with experimental results indicates close similarities between theoretical and experimental curves in the yielding region but significant deviation in the plastic region.

2. Experimental methods

2.1. Sample preparation

All the specimens were produced on the DMD505 machine operating with a CO_2 laser that can generate beam power up to 5 kW. Like in all LAAM processes the composition and micro-structure of any part or coating created on DMD machine depends on a set of machine and process parameters, which are controllable during operation and the final outcome depends on their optimum combination. The most important parameters are laser power (in watts), laser beam diameter (in millimetres), laser scanning speed (in mm/s) and powder feed rate (in gm./min). Sometimes a term "Specific Energy" is defined as: laser power/(beam diameter × processing speed) [19]. The value of specific energy for the deposition varies from 375 to 1000 Joules/mm^2. Riza et al. [20] have earlier described how the combination of DMD process parameters affect the prospects of developing different types of structures particularly when achieving the accuracy of dimensions comparable to the minimum possible width of laser beam and maximum possible height of deposited layer. Table 1 shows the optimized DMD process parameters for creating 316L SS and H13 TS solid and porous specimen.

It is noted from the material properties literature [21] that 316L SS and H13 TS have significant differences in their mechanical properties which are not entirely independent of their chemical composition. The chemical composition of the two powders obtained from supplier's data is presented in Table 2.

In total 24 solid and porous specimens were produced by the laser assisted DMD process, which ascribes 3 specimens per material per type for each test. The porous structures are basically designed keeping in view the percentage of porosity that can be maximally achieved for small specimen (<10 mm diameter) within the parameters of DMD. This consideration is numerically exhibited in Table 3. It should also be noted that the process parameters presented in Table 1 are selected with this constraint in mind because if only solid specimens were to be considered, then much higher laser power, track speed and powder feed would be used.

If proven tough, stiff and strong then porous structures can serve as the building blocks for developing sandwich and cellular structures. The shape of cavities is semicircular for quasi-static testing and quarter circular for dynamic testing. Subsequent to cladding, the specimen are turned to the required size and then parted off from the mild steel substrate. Fig. 1(a) shows the specimens each for porous H13 and 316L materials for dynamic testing along with the corresponding CAD model. Fig. 1(b) shows the specimens used for quasi-static testing along with its CAD model.

Three identical specimens were tested for each case to get average results. Table 3 presents the necessary data including length and diameter for all the finished parts (porous +solid) that are used in this experimental investigation.

Table 1
DMD Process parameters.

Parameter	Unit	Value
Laser energy	Watts	500
(Beam) S-Focus[a]	Degrees	−17
Scan speed	mm/min	30–80
Powder feed rate	g/min	3–4
Cover gas flow (Argon)	Litres/min	2
Carrier gas flow (Argon)	Litres/min	7
Carrier gas flow (Helium)	Litres/min	2
Shielding gas flow (Argon)	Litres/min	18
Shielding gas flow (Helium)	Litres/min	5
Shaping gas flow (Argon)[b]	Litres/min	10

[a] S-focus is an optical machine parameter that controls the beam spot size. For the value −17, beam spot size is from 0.9 to 1 mm.

[b] Shaping gas is also called nozzle gas that shapes the powder stream coming out of the nozzle into the focus of laser beam and subsequently deposited on the substrate after melting.