Dynamic Behaviour of High Strength Steel Parts developed through Laser Assisted Direct Metal Deposition

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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 CO₂ 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.

Keywords: Dynamic behaviour, high strain rate, direct metal deposition, high strength steels

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 2m x 1m 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].

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 CO₂ laser that can generate beam power up to 5kW. 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/sec) and powder feed rate (in gm./min). Sometimes a term “Specific Energy” is defined as: laser
power/ (beam diameter x processing speed) [19]. The value of specific energy for the deposition varies from 375 to 1000 Joules/mm². 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.

2.2 Testing Procedures:
Out of the total, 12 finished specimens were then tested for high strain compressive loading on a Split Hopkinson Pressure Bar (SHPB). This equipment provides the opportunity to test materials at strain rates from 50 s⁻¹ to around 10⁴ s⁻¹, which is sufficient to simulate ballistic impacts, explosion scenarios and high speed crashes [22]. Figure 2 illustrates the mode of operation of SHPB and the dimensions of actual setup on which the experiment was performed [23].

The Split Hopkinson Pressure Bar or Kolsky compression bar is simply a combination of bars in which the elastic stress wave is generated by impact of the striker (energized by high pressure gas) on the incident bar. Since the tested parts are made from high strength steel alloys, a maximum available gas pressure of 0.25 MPa was used to create high strain rate impacts at more than 2000 s⁻¹. When the compression wave in the incident bar propagates to the interface between the incident bar and the specimen, part of it is reflected back into the incident bar while the rest is transmitted into the specimen and compresses the specimen. The interaction of the stress waves in the specimen with the specimen/transmission bar builds the profile of the transmitted signal. By suitable measurement techniques involving strain gauges, oscilloscopes and data acquisition system and by the application of elastic wave theory, details of the applied disturbance can be reconstructed. Since the bar remains elastic, it can be used to measure either loads or displacements or both [24, 25].
The signals in the form of incident, transmitted and reflected waves, which eventually transform into stresses and strains, are measured by the strain gauges. Strain gauge A measures the incident and reflected waves while transmitted wave signals are measured by strain gauge B. Fig. 3(a) shows all these waveforms and their sequential relationship along the time scale, while Fig. 3(b) represents the matched reflected and transmitted waves which actually provide the values of stress and strain respectively.

In all, 12 parts were tested on a servo-hydraulic MTS 7973 testing machine of 250 kN capacity for quasi static testing. The machine is equipped with load cells, extensometers and the data acquisition software that provides the load vs. displacement graph simultaneous to the loading and deformation of the specimen between the moving platens. The strain rate during the quasi-static tests was maintained at 0.001 s\(^{-1}\).

3. Results and Discussion

The stress-strain curves are derived from the quasi-static and high strain rate dynamic testing for solid and porous specimen of 316L stainless steel and H13 tool steel. High strain rate dynamic curves provide a good insight into the toughness, dynamic yielding strength and impact resistance of the laser deposited material but contain insufficient information for behaviour in the elastic/ static yielding region and on response to continuously applied loading with small strain rates. This gap is filled by the quasi static curves which analyse the behaviour of two grades of high strength DMD generated steel alloys under large compressive loads in (i) the yielding region and (ii) up to 40% strain, which is considered to be the extreme level of true strain that can be endured at satisfactory performance levels.

Due to vastly different types of responses to compressive loading at quasi static strain rates (0.001 s\(^{-1}\)) and high dynamic loading strain rates (> 2000 s\(^{-1}\)), the results are described in separate sections.

3.1 High Strain Rate Dynamic Testing:

Split Hopkinson Pressure Bar (SHPB) is used to develop stress strain curves for 316L and H13 laser cladded specimens of solid and porous types. Main feature of this setup is to check the response of specimen under high strain rate conditions simulating high velocity impacts. The initial dimensions of the specimen tested were 9 mm outer diameter and 6.25 mm length. The dimensional variations during sample preparation were kept within ± 0.1 mm. Careful measurement of dimensions after the impact, as shown in Table 4, indicate the trends representative of very high material strength and superior stiffness. The volumetric strain for H13 is three times less than 316L which is in accordance with the values of strength of H13 to be 3 times the strength of 316 L as can be observed from manufacturer’s data [21].

In SHPB system, the impact was initiated through a striker bar excited by a gas pressure of 0.25 MPa that transferred its energy to the incident bar, which in turn generated an impact velocity of 21.98 m/s. For a specimen of length 6.25 ± 0.1 mm, this amounts to a nominal strain rate (NSR) in the range of 3461-3573 s\(^{-1}\). When equilibrium state is achieved, the actual strain rate is a function of wave propagation velocity and the amplitude of reflected wave. Reflected wave inherently carries the information regarding deformation of the specimen struck by the incident bar and thus the plot of strain rate vs. time illustrates the extent of deformation which the specimen undergoes in response to the impact and the mode of dissipation of impact wave. Higher values of actual strain rates (ASR) indicate more deformation and lesser time to zero value denotes better impact absorption capability or higher toughness. Fig. 4 shows the values of strain rate, true stress and true strain are calculated and plotted against time for all the four types of specimens. Strain values are scaled up by a factor of 1000 while strain rates are scaled down by a factor of 5 to make possible the meaningful presentation of three quantities on the same graph.

A close study of all the graphs presented in Fig. 4 leads to the following results:
a) As expected, according to material properties, DMD generated H13 TS (tool steel) specimen is stronger and stiffer than 316L SS (stainless steel) specimen. The solid H13 TS shows a maximum actual strain rate (ASR) of 2228 s\(^{-1}\) while 316L goes up to 3391 s\(^{-1}\) under same values of impact velocity.

b) For solid H13 specimen, the time taken by strain rate to drop to zero value is just 20 µs as compared to 100 µs for solid 316L. This indicates demise of reflected wave and clearly proves high impact energy absorption capability of laser DMD generated H13 TS specimen.

c) For porous specimen of both material types, the actual strain rate (ASR) values are higher than the solid parts and in fact reach 3800 s\(^{-1}\) which is greater than the applied strain rate. This may be due to the resonating effects in the reflected wave and is expected due to presence of cavities in the porous parts.

d) There is a distinct difference in the manner in which the strain spike dies down among the two materials. In H13 TS, the spike instantly gets back to nearly zero with subsequent negligible vibrations, but in 316L SS, the ASR attains zero value gradually after a delay of 0.001 s. It clearly proves the superior impact resistance and energy absorption capability of laser cladded H13 TS.

e) When compared to the variation of stress vs. time, the values of strain in all cases is lagging by an interval of 20µs. This is also accompanied by an initial interval of zero strain. This behaviour corroborates with the behaviour in quasi static testing and strongly suggests the presence of micro-porosity in the laser generated specimen. The presence of microscopic size pores and voids, a phenomenon generally referred to as micro-porosity, is a well-known fact for laser generated structures. Dadbaksh et al [26] clearly mentioned the presence of micro-pores in the stainless steel parts produced by selective laser melting. Yasa and Kruth [27] also reported a presence of 1-2% micro-porosity in laser generated 316L SS parts. When cut and viewed our 316L solid specimen under high magnification, the SEM micrographs, as shown in Fig. 5, also illustrate the presence of voids and pores at the microscopic level in steel parts produced on DMD.

f) The peak value of stress is in the range 1250-1300 MPa for solid specimen and in the range 925-975 MPa for porous parts. The difference in stress values is accompanied by an increase in strain from 0.0591(solid) to 0.0969 (porous) for H13 and from 0.161(solid) to 0.194 (porous) for 316L parts. These values prove the capability of porous specimen to absorb the impact energy by deforming more at lower stress values. This is an indicator that highlights the advantageous use of porous structures in preparing blast and explosion proof lightweight structures without sacrificing overall strength.

g) Another noticeable aspect is the time at which stress values become the maximum. For H13 TS, this time is synchronous with the peak strain rate but in all other cases, this peak is achieved at the end of second region or before initiation of stress drop down. This means that for both the porous and 316L solid specimen deformation and stress builds up simultaneously until the impact is absorbed, while for H13 solid part major portion of impact was absorbed as soon as the impact was received.

Fig. 6 shows the graphs of true stress and true strain, which are calculated using elastic wave theory and plotted for all the four types of specimens. There are three distinct and noticeable regions of the stress strain curves explained as follows:

a) The first region in dynamic stress-strain curves in Fig. 6 exhibits a rapid rise of stress which is observable in every curve and corresponds to the almost instantaneous peak surge in strain rate at 0.003 s due to impact of incident bar. In this initial region, true strain has a range of 0 to 0.02 during which H13 TS shows stress rise up to 1250 MPa while the maximum value for 316L SS is 800 MPa. Stresses created by the impact are within the elastic range of H13 TS but much beyond the yielding stress of 316L SS. Therefore, we see the peculiar manner in which the stress rises to its peak value in 316L solid and porous specimen. For 316L solid part, the stress rises at constant slope up to a value of 545 MPa which corresponds to the ultimate strength of material and then the graph shows an increase in stress up to 801 MPa but strain also increases to 2.14%. This is the initial region of work hardening.
b) Second region in Fig. 6 is the stress plateau after impact and is accompanied by increasing strain. It encompasses the zones of elastic and plastic deformations both, as the incident pressure wave is transmitted through the specimen. Another noticeable factor in this region is that apart from H13 TS solid specimen, value of stress is increased with respect to the value in first region. This is the zone of energy absorption and plastic deformation.

c) Third region in Fig. 6 is when stress drops to zero after the termination of impact related effects and later accompanied by recovery of elastic strain. For H13 solid specimen, maximum strain is 0.0591 subsequently recovered to 0.0464, which remains as the final plastic strain. On the other hand 316L SS is compressed to a strain of 0.161, from where it recovers to the final value of 0.1478. As the ultimate strength of 316L is 3 times less than that of H13, therefore, the values of final plastic strain are corresponding to the ratio of strengths like the volumetric strain ratio given earlier.

Solids and porous specimens show different behaviours related to absorption of impact. The initial region for porous specimen indicates a higher strain which is 4% for H13 and 3.5% for 316L. In the beginning high strain is due to the presence of cavities, but when the pores close down and the walls of cavities come closer, value of stress continues to rise. In between first and second region the stress varies from 815 to 1072 MPa for H13 and from 748 to 893 for 316L porous specimen. The values of maximum strain as the stress approaches zero are 17.78% for H13 and 22.5% for 316L respectively. Strain recovery is 1.2% for both H13 and 316L porous parts. This demonstrated behaviour of very little stress variation during absorption of impact and extended region of strain hardening without rupture or crushing is suitable for energy absorption and dissipation applications.

The compressive dynamic behaviour observed and presented in Fig. 6 when compared with commercial grade and wrought steels under high strain rate compressive loading reveals important results. For austenitic steels, sufficient data are available describing their dynamic characteristics under high strain rate compressive loading with temperature variation. Nemat-Nasser et al [28] have used enhanced Hopkinson’s bar technique to determine true stress vs true strain curves for austenitic steels designated as AL-6XN. The AL-6XN is different from common austenitic steels in that they contain nitrogen for strengthening in addition to higher percentages of nickel and molybdenum. The samples were cut by electro-discharge machining (EDM) from commercially available plates. These are tested under strain rates ranging from 0.001s$^{-1}$ to 8000 s$^{-1}$ while initial temperatures vary from 77K to 1000K. Another series of such test results are available from the investigation of Lee et al [18], who examined cold drawn and annealed bars of commercially available 316L biocompatible stainless steels. They investigated the compressive dynamic behaviour under strain rates ranging from 0.001s$^{-1}$ to 5000 s$^{-1}$ while changing the temperatures between 25 and 800°C. It must be mentioned that such type of data are not available for H13 tool steels to the best knowledge of authors.

Based on the comparison with these two sets of experimental data it is found that the laser generated steels are inferior in strength to commercial and wrought stainless steels, but comparable to AL-6XN steels. For AL-6XN samples, at 296K and strain rate of 3500 s$^{-1}$, true stress is reported as 950 MPa corresponding to a true strain of 0.1. While at the same true strain and strain rate of 3000 s$^{-1}$ true stress is approximately 1150 MPa for the commercial grade 316L SS at temperature of 25°C. The values mentioned in [24] are in exact correspondence with those shown in Fig. 6 for 316L solid specimen, but less than the true stress values found for wrought and heat treated 316L bars. The comparison cannot be made with H13 tool steel, because at these strain rates the H13 solid specimen do not experience a true strain of 0.1. However, for porous H13 parts, true stress at 0.1 true strain is around 950 MPa, which is almost similar to the strength values exhibited by solid 316L specimen. Since the steel specimens tested in this investigation do not undergo any heat treatment operation, therefore, the comparative results are extremely encouraging from the viewpoint of compressive strength.
3.2. Quasi Static Stress Strain curves:

The dynamic curves provide very useful information regarding stress strain behaviour at high strain rate dynamic conditions but are rarely useful for understanding the elastic behaviour and static yielding of the parts. Therefore, solid and porous specimens made of two steel types were examined under uniaxial and continuously applied compressive loads at strain rate of 0.001 s⁻¹. The stress strain relationship covers elastic and plastic regions both. A noticeable observation during testing was that the solid pieces were almost flattened (crushed) by the compressive forces without breaking or fracture, but porous pieces showed lesser length reduction due to internal space available for lateral expansion within the cavities. Fig. 7 shows the true stress versus true strain curves plotted for all four types of specimen.

Some important observations inferred from these curves which are not available from the dynamic curves are presented as follows.

a) All the curves are non-linear in elastic and plastic regions both as expected from the stress strain behaviour of high strength steel alloys [29]. The four curves, although differing with each other in numerical values of yield strength and modulus of elasticity, display a common trend of dual modulus of elasticity in the region before yielding. The exhibition of dual modulus in the stress strain curve can be explained in terms of micro-porosity that is almost always present in parts which are produced by sintering or melting of powder. The inherent micro-porosity may act as a “notch” and results in abrupt change in slope of stress-strain curve within the yielding region [30].

b) The presence of dual slope within the yielding region generates two values of Young’s modulus ‘E₁’ and ‘E₂’ which are evaluated and presented in Table 4. E₁ exists up to 0.32 % strain while E₂ covers the range from 0.35 to 3% strain. Values of E₁ for both the materials are approximately half as compared to E₂. It means appreciable deformation in the beginning without significant values of stress. The resulting slope of both the curves confirms that the value of compression modulus of the produced materials is quite low in comparison to the values found in manufacturer’s catalogues and handbooks for the commercially available grades.

c) There is not much information available on the exhibition of low modulus of elasticity for laser cladded steels but very recently de Lima and Sankare [31] have reported the exactly same behaviour for specimen produced by laser based additive manufacturing of 316L powder on the substrate of the same material. Although the values reported in this paper are not that low but in comparison to those for rolled sheets are still low enough as is clearly evident from Table 5.

d) Since high strength steel alloys do not exhibit a distinct yield point which prompts the use of 0.2% proof stress as a measure of yield strength for such materials [32]. The values of 0.2% proof stress for 316L SS is in the range 250 -325 MPa and for H13 TS, 0.2% proof stress is evaluated to cover the range 1225 - 1300 MPa which is 30% lesser than the yield strength of quenched H13 tool steel. And since these values show good repeatability, it proves that the steels “produced” by laser assisted DMD process are competitive enough in strength and ductility values to commercially available high strength steel alloys.

An important characteristic of “strengthening under dynamic loading” is also evident when static and dynamic curves are viewed together. Wu and Jiang [33] reported 74% increase in crush strength of honeycomb structures under dynamic loading as compared to quasi-static loading conditions. Deshpande and Fleck [34] mentioned the fact, based on substantial research evidence, that compressive strength of metallic foams remains insensitive to applied strain rates of 1000 s⁻¹. In our investigation, this behaviour is significantly evident for both 316L and H13 solid and porous parts. In dynamic curves, the stress of 800 MPa soon after impact is accompanied by a strain of 2.2%, while under quasi-static loading this value of stress is achieved after 9.7% strain. For H13 this dynamic hardening effect is also very prominent as stress level reaches up to 1192 MPa at 0.1% strain while under quasi-static loading equivalent values are obtained.
at strain of 4.7%. This effect may be due to the sudden action of impact of dynamic loading, which brings the part beyond elastic limit into the regions of strain hardening almost instantaneously. This causes the expanded regions of static curve to squeeze and generate a curve with much steeper slope and thus more strength and hardening of the loaded material.

4. Constitutive Relationships

Due to significantly different behaviour of high strength steel alloys in comparison to carbon steels, there is a continuous research for developing mathematical models that can constitute the stress-strain characteristics of these metals. Rasmussen [32] in his detailed analysis developed relationships based on the classic Ramberg-Osgood relationships [35], which make use of the Ramberg-Osgood parameter (m) to extend the linear elastic region to include plastic deformation. Eq. (1) shows Rasmussen’s full range stress strain relationships that can model the stress strain behaviour of stainless steels under tension as well as in compression in a piecewise manner while employing only three parameters, which include initial Young’s modulus, 0.2% proof stress and 0.01% proof stress.

$$
\varepsilon_R = \begin{cases} 
\frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{\sigma_{0.2}} \right)^n & \text{for } \sigma \leq \sigma_{0.2} \\
\frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u \left( \frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}} \right)^m + \varepsilon_{0.2} & \text{for } \sigma > \sigma_{0.2}
\end{cases} \tag{1}
$$

In these equations the exponent ‘m’ is given as: $m = 1 + 3.5 \frac{\sigma_{0.2}}{\sigma_u}$. The modulus to the curve at 0.2% proof stress is estimated as: $E_{0.2} = \frac{E_0}{1 + 0.002 \left( \frac{n}{0.2} \right)}$ where $n = \frac{\ln(20)}{\ln(\sigma_{0.2}/\sigma_{0.01})}$ and $\sigma_{0.2} = \frac{\sigma_{0.2}}{E_0}$.

Ashraf et al [36] also made use of the Ramberg-Osgood relation to present equations that define strain as a function of stress in two similar steps. In every case the initial range of strain exists from 0 to 0.2%, while the second equation covers every strain value beyond 0.2%. The equations derived by Ashraf et al [36] are more suitable for modelling stainless steel specimen under compression, because these take into account two very important features of high strength steel’s behaviour under compressive loading, which are (i) absence of ultimate stress and strain ($\sigma_u$ and $\varepsilon_u$); instead these values are substituted with 1% proof stress ($\sigma_{1.0}$) and a correction factor, and (ii) inclusion of strain hardening co-efficient ($n_{(0.2:1.0)}$). Later Quach et al [37] combined the analyses of Rasmussen and Ashraf et al to develop stress strain equations for stainless steels spread over three regions. First zone is same but second zone is from 0.25 to 2% and the additional third region extends from 2% to all greater values. The equations covering stress range from $\sigma @ \varepsilon < 0.2$ to $\sigma @ \varepsilon > 2.0$ as presented by Quach et al [37] are presented collectively in Eq. (2):

$$
\varepsilon_Q = \begin{cases} 
\frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{\sigma_{0.2}} \right)^n & \text{for } \sigma \leq \sigma_{0.2} \\
\frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left[ 0.08 + (\sigma_{1.0} - \sigma_{0.2}) \left( \frac{1}{E_0} - \frac{1}{E_{0.2}} \right) \right] \left( \frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}} \right)^{n_{0.2:1.0}} + \varepsilon_{0.2} & \text{for } \sigma_{0.2} < \sigma \leq \sigma_{2.0}
\end{cases} \tag{2}
$$

Based on the models proposed by Rasmussen [32] and Quach et al [37], the stress-strain curves are plotted for 316L SS specimen and compared with the experimental true stress vs. true strain curve with the plots shown in Fig. 7(a). Since in Rasmussen equations the expressions for $\sigma_u$ and $\varepsilon_u$ are developed from the test
data for tensile coupons, therefore, for compressive strains these are adjusted according to the equations given by Quach et al and thus the ultimate compressive stress and strain is used according to the relationships as given in Eq (3):

$$\sigma_{u}^{com} = \sigma_{u}^{ten} (1 + \varepsilon_{u}^{ten})^2 \quad \text{and} \quad \varepsilon_{u}^{com} = 1 - \frac{1}{1+\varepsilon_{u}^{ten}}$$  \hspace{1cm} (3)

For H13 TS, the theoretical and experimental curves are totally out of conformity and this mismatching is particularly due to huge difference between 0.2% proof stress and $E_0$. The parameters obtained from the experimental data and used in plotting the theoretical curves are $E_0 = 38.4$ GPa, $\sigma_{0.2} = 325$ MPa, and $\sigma_{0.01} = 51$ MPa. The values of Ramberg-Osgood parameter and the strain hardening coefficient are evaluated as 1.6863 and 7.926 respectively. Comparing to the values available in [32] and [35], it is obvious that ‘$n$’ is too small and $n'_{0.2,1.0}$ is exceedingly high; a behaviour that is also evident from the graphical comparison.

It is important to note that in mathematical modelling of the behaviour of laser cladded 316L SS, the effect of primary yielding region is kept to a minimum in calculation of main parameters. As stated earlier, the primary yielding signifies the presence of micro-porosity, an effect that is not present in stainless steels produced by forming and forging. The theoretical and experimental curves are in close proximity up to 2% strain, after which the deviation becomes prominent. It can be observed that, as shown in the magnified view of the yielding region of the experimental curve in Fig. 8 (b), the deviation is mainly due to high non-linearity and low compression modulus in the primary yielding zone for experimental curve, but as the values move beyond 0.5% strain, differences between mathematical model and experimental curve are narrowed to within +10%. Rasmussen curves show very little strain hardening while Quach curves indicate significant strain hardening effects. But the actual strain hardening rate as shown from experimental data is much higher than the values suggested by the mathematical model. This may be due to high hardness of the part (161 HV50) and low modulus of elasticity. This fact can be observed in the stress-strain power law for plastic region of deformation.

5. Conclusions

Laser assisted direct metal deposition process provides a unique technique for producing materials of desired shape and configuration merely through CAD control and eliminating otherwise necessary tooling. Two high strength steel alloys 316L SS and H13 TS were used in powder form to create cylindrical specimen and tested for strength and ductility under quasi static and high strain rate dynamic conditions. Both the specimen showed very good ability to withstand the axial load and to bear the impact load and were found to be close to most of the mechanical properties obtained for these alloys manufactured commercially. A noticeable shortcoming from manufacturing aspect is the lack of any forming and shaping forces involved during production of part that effectuates micro-porosity and fractional non-homogeneity in the microstructure. Due to this and absence of any post-processing operation, some inconsistencies are observed in mechanical properties. But the variations observed are not entirely random causing the specimen from the same material to behave differently under similar testing conditions. Instead the observed variations during quasi static testing are confined within ±10% of the average values presented in this paper. Repeatability in dynamic testing is still better and restricted to ± 6% of the average values. The values for 0.2% proof stress and maximum elastic strength are very close to those available for commercial grade steels but the noticeable departure is low value of modulus of elasticity. This can be improved by heat treatment considerably.

The stress strain curves obtained are highly valuable and demonstrate the capability of DMD system to produce parts of high strength and stiffness that can withstand impact loads at high strain rate. This advantage becomes more prominent when viewed in the backdrop of specimen being tested in as-cladded condition without any heat treatment to alleviate residual stresses or enhance strength and ductility. This investigation opens the door of employing superior mechanical properties of H13 in applications much
diversified and not limited to only tool manufacturing. For 316L SS, the behaviour can be regarded as highly satisfactory, because it bears the impact loads without fracture up to the stress values, which are much higher than the ultimate stress quoted in manufacturer’s catalogue.

Acknowledgements

Authors wish to thank Mr Girish Thipperudruppa for his diligent contribution in laser cladding and sample preparation and Mr Kia Rasekhi for his valuable assistance in quasi static testing of the specimen.

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Table 1: DMD Process parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy</td>
<td>Watts</td>
<td>500</td>
</tr>
<tr>
<td>(Beam) S- Focus*</td>
<td>Degrees</td>
<td>-17</td>
</tr>
<tr>
<td>Scan speed</td>
<td>mm/min</td>
<td>30-80</td>
</tr>
<tr>
<td>Powder feed rate</td>
<td>g/min</td>
<td>3–4</td>
</tr>
<tr>
<td>Cover gas flow (Argon)</td>
<td>Litres/min</td>
<td>2</td>
</tr>
<tr>
<td>Carrier gas flow (Argon)</td>
<td>Litres/min</td>
<td>7</td>
</tr>
<tr>
<td>Carrier gas flow (Helium)</td>
<td>Litres/min</td>
<td>2</td>
</tr>
<tr>
<td>Shielding gas flow (Argon)</td>
<td>Litres/min</td>
<td>18</td>
</tr>
<tr>
<td>Shielding gas flow (Helium)</td>
<td>Litres/min</td>
<td>5</td>
</tr>
<tr>
<td>Shaping gas flow (Argon)**</td>
<td>Litres/min</td>
<td>10</td>
</tr>
</tbody>
</table>

*S-focus is an optical machine parameter that controls the beam spot size. For the value -17, beam spot size is from 0.9-1 mm.

**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.

Table 2: Chemical Composition of metallic powders used in Laser Cladding on DMD

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition % wt.</th>
<th>Iron</th>
<th>Chromium</th>
<th>Molybdenum</th>
<th>Nickel</th>
<th>Manganese</th>
<th>Silicon</th>
<th>Carbon</th>
<th>Other</th>
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<tbody>
<tr>
<td>A. 316 L stainless steel powder supplied by SULZER Metco Australia</td>
<td>62-72</td>
<td>16 -20</td>
<td>2 - 4</td>
<td>10 - 14</td>
<td>1</td>
<td>2-3</td>
<td>0.03</td>
<td>&lt;0.5</td>
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<tr>
<td>B. H 13 tool steel powder supplied by Alloys International Australasia pty Ltd.</td>
<td>Balance</td>
<td>5 - 7</td>
<td>1.5 - 2</td>
<td>1 - 2</td>
<td>0.4</td>
<td>1</td>
<td>0.35</td>
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</table>

Table 3: Average Specimen Size (in mm) Used in Testing

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Quasi Static Testing</th>
<th>% of Solid Volume</th>
<th>High Strain rate testing</th>
<th>% of Solid Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Outer Dia.</td>
<td>Length</td>
<td></td>
<td>Outer Dia.</td>
</tr>
<tr>
<td>H13</td>
<td>Solid</td>
<td>4.06</td>
<td>3.89</td>
<td></td>
<td>8.96</td>
</tr>
<tr>
<td>H13</td>
<td>Porous</td>
<td>8.1</td>
<td>4.53</td>
<td>73.43</td>
<td>9.02</td>
</tr>
<tr>
<td>316L</td>
<td>Solid</td>
<td>4.03</td>
<td>3.71</td>
<td></td>
<td>8.97</td>
</tr>
<tr>
<td>316L</td>
<td>Porous</td>
<td>8.06</td>
<td>3.91</td>
<td>73.16</td>
<td>8.95</td>
</tr>
</tbody>
</table>

Table 4: Specimen dimensions as measured after dynamic testing

<table>
<thead>
<tr>
<th>Type of Specimen</th>
<th>Outer Diameter (mm)</th>
<th>Length (mm)</th>
<th>Change in volume (mm³)</th>
<th>% change in volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>H13 TS solid</td>
<td>9.19</td>
<td>5.97</td>
<td>-1.6078</td>
<td>-0.4044</td>
</tr>
<tr>
<td>H13 TS porous</td>
<td>10.31</td>
<td>5.82 (*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>316L SS solid</td>
<td>9.54</td>
<td>5.49</td>
<td>-5.1807</td>
<td>-1.303</td>
</tr>
<tr>
<td>316L SS porous</td>
<td>10.81</td>
<td>5.43 (*)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*For porous parts it is very difficult to calculate accurate changes in volume by measuring exterior dimensions only due to flow of material inside the cavities.
Table 5: Young’s Moduli in the Yielding elastic region

<table>
<thead>
<tr>
<th>Material</th>
<th>Zone designation</th>
<th>Range in % strain</th>
<th>Young’s Modulus (Experimental) (GPa)</th>
<th>Young’s Modulus - commercial grade alloys (GPa)[25]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel 316L</td>
<td>Primary Yielding</td>
<td>0 to 0.32</td>
<td>(E₁) 17</td>
<td>193 – 200 (Annealed)</td>
</tr>
<tr>
<td></td>
<td>Secondary Yielding</td>
<td>0.35 to 2.7</td>
<td>(E₂) 38</td>
<td></td>
</tr>
<tr>
<td>Tool steel H13</td>
<td>Primary Yielding</td>
<td>0 to 0.3</td>
<td>(E₁) 26</td>
<td>210 (Hot Worked)</td>
</tr>
<tr>
<td></td>
<td>Secondary Yielding</td>
<td>0.35 to 2.2</td>
<td>(E₂) 45</td>
<td></td>
</tr>
</tbody>
</table>

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(a) Normal view (b) Magnified view of the yielding region of experimental curves
Research Highlights

• Dynamic compressive behaviour of laser generated high strength steels on DMD
• Solid and porous DMD parts subjected to high strain rate and quasi-static loading
• Solid and porous specimens show different behaviour related to absorption of impact
• Significant strain hardening under dynamic loading for both H13 and 316L steels
• Novel energy absorption behaviour of porous steel specimens