The role of laser in manufacturing of shape memory alloy (sma)

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Abstract. Shape Memory Alloys are widely used smart materials in recent times for various applications from aerospace to biomedical field. Shape Memory Alloy (SMA) is made of mixture of different metal powders (Ni-Ti with 50 – 50 Wt% (approximate) can give Nitinol) and/or by using filler metals. However, fusing the selected powder mixture and making as SMA is a challenging task. Researchers used various techniques for making SMA which can be classified into two major categories likely casting method and powder metallurgy method. Laser power to make SMA is widely used by most of the researchers. These processes are further classified by conventional and non-conventional methods. Under this method various classification like Direct Laser Melting, Selective Laser Melting, Laser Sintering and Laser Cladding are available. In this article, the above-mentioned production methods using laser as major source are studied carefully. The advantages and limitations are also discussed on justifying the suitability of processing SMA by lasers. Along with their limitations the influence of each parameter is focused. Finally, a conclusion is made based on this detailed study.

1. Introduction

In olden days most of the bioimplants were built with Stainless Steels (SS) family. The presence of the chromium in Stainless Steel creating the problem with living tissue [1-2]. After that titanium alloys (Ti-6Al-4V) were used instead of stainless steels. Similarly, the alloying element vanadium and aluminium present in Ti-6Al-4V also making the same problem [3-4]. Also, the major expectation like Stress-strain behaviour, Effective modulus and Torqueability are not compromised with stainless steel and titanium materials [5]. In addition to this, biomedical devices are looking for perfect biocompatible materials which can satisfy with bio-functionality and biocompatibility. The lifetime and maintenance of the bio-components (bioimplants and biodevices) are also to be focused along with above-mentioned properties. These points are clearly identifying that Stainless Steel (SS316L) and titanium (Ti-6Al-4V) are not suitable for biomaterials application [6-11].

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All these above drawbacks created attention towards Shape Memory Alloys for constructing the bio-components. This material is widely used in chinese market [12]. Among all SMA, Nitinol (Nickel-Titanium) is most preferable for above-mentioned applications which fulfills the expected properties. The production of SMA is most challenging task, as titanium is having good affinity with atmosphere content if the processing temperature is exceeding 400°C [13-14]. The secondary challenge is maintaining the favourable phases to obtain the shape memory effect. The various methods like Selective laser melting (SLM), also known as direct metal laser melting (DMLM) or Laser Powder Bed Fusion (LPBF) are focused. In the present study, the usage of laser in the production of SMA is discussed briefly.

1.1. Laser Engineered Net Shaping (LENS)
Krishna et. al discussed the drawback of the conventional manufacturing process and their effects in concern with NiTi SMA. The compressive strength of the LENS processed samples were showed excellent performance [15]. A post-processing heat treatment was needed for these SMA in order to compensate for the metallurgical changes. Griffith et. al studied the LENS (Laser Engineered Net Shaping) process for fabricating the metallic components [16]. This is the key study for all the researchers for implementing this process for a variety of materials (Fig. 1).

![Figure 1. Laser Engineered Net Shaping (LENS) process [17].](image)

Another work by Korinko showed the possibility of additive manufactured components through LENS. Few samples were repaired using this LENS method and all the repaired samples were showed satisfying results [18].
Baran and Polanski studied the laser scanning speed on their effect on the fabrication of SMA. It was found that laser velocity has a significant influence on the NiTi microstructure. The expected properties like shape memory effect were lost with lower scanning speed. The cooling rate and chemical composition were the two major parameters affect the microstructure of NiTi. It was reported that the LENS method is an effective method for fabricating complex parts and complicated
materials compositions [19]. Mudge and Wald reported the flexibility of LENS for handling various operation including repairing the metallic components.

In addition to flexibility, effective cost saving and controlling the loses were achieved by LENS method [20]. Another advantage of this LENS was the interface with CAD programming. Krishna et al studied the porous Ni+Ti SMA manufactured by LENS method. The density and power in terms of energy were correlated with each other. Nominal results were achieved from the SMA having the porosity ranging from 12% to 36%. It was concluded that the presence of porosity is the need for biomedical applications [21]. Bernard et al fabricated the Ni-Ti SMA with 50:50 ratio using the particles of Ni and Ti powders. Commercially pure titanium of 3 mm block is used as a base substrate. Using the Nd-YAG laser various porous with different density was made. LENS method is used to deposit the layers. This layer formation is repeated and again to complete the entire model [22]. The complete model was built inside the controlled atmosphere to avoid contamination.

1.2. Selective Laser Melting (SLM)

Wang et al made a different attempt for producing SMA by layer by layer formation. The microstructure of the layers found to be austenite and martensite [23]. It was concluded that this layer by layer manufacturing method is an effective way of manufacturing the SMA as shown in figure 2.

![Figure 2. Selective Laser Melting (SLM) process [24].](image)

Habijan et al discussed the additive manufacturing technology such as selective laser melting. It was also reported that instead of removing the materials from the components laser-based layer by layer manufacturing resulted in good geometrical flexibility [25]. Yadroitsev et al also stated the same layer by layer technique for manufacturing SMA by SLM [26]. Shishkovsky et al investigated the effect of exothermic powder mixing with the help of laser. A separate image analysis software was used for the formation of the microstructure in the SMA. It was found that increasing the laser power the wall thickness of the component was decreased [27]. Haberland et al studied the selective laser melting process for manufacturing SMA through additive manufacturing. The optimization of the laser parameters was studied carefully for getting a perfect SMA [28]. A successful fabrication with expected properties was achieved by additively manufactured SMA. Karamooz-Ravari et al studied the SMA behaviour produced by selective laser melting process. The elastic behaviour of the SMA is explained and compared by using the micro-plane theory [29].

A model was made and to cross-check the mathematical model the SMA was manufactured by the above-mentioned process. Oliveira et al investigated a comparative study with SMA. Two different processes such as micro joining and additive manufacturing were taken. The impact of these process was observed through XRD by analysis of their microstructure [30]. Ma et al studied the additive
manufacturing of SMA using Selective Laser Melting. The formation of intermetallic and lattice structures [31]. A model was developed for understanding the thermal – stress produced during the manufacturing process. The starting and finishing temperature of austenite and martensite were identified for the SMA. Moghaddam et al studied the additive manufacturing process using laser power source. SLM technique was used for building the layers. At various locations with an angle (0°, 45° and 90°) tensile samples were prepared [32]. The samples prepared with horizontal orientation was showed more strength. Finally, it was proved that the samples prepared from angle 45 orientation revealed minimum strength. Along with scanning strategy also playing a major role in obtaining maximum results.

Elahinia et al reported that careful heat treatment of NiTi materials can retrain their properties after the manufacturing process [33]. Such a process was used to get a significant modification of their mechanical properties and microstructures. The material titanium is very sensitive to the temperature. So, heat treatment can have a significant effect. Selective Laser Melting (SLM) is suggested for manufacturing the medical components with complicated size. Man et al studied the porous SMA of nickel-based material. Using the SLM process a porous layered structure was made over the SMA. This porous was aimed to increase the biocompatibility of the SMA [34]. The change in the composition of the Ni near its surface was identified due to the Laser process. Mullen et al fabricated a porous structure using the titanium materials. SLM technique was used for fabricating the porous structure of functionally graded parts. An optimal component was fabricated, and the fabricated bone structure was supporting the bone growth functions [35]. These significant outputs were helped to produce orthopaedic devices successfully.

2. Discussion
In this section, the widely used laser method for fabricating the nickel-based SMA is briefly discussed with various research work. All the laser-based SMA manufacturing are mainly classified under two classification. First one is Selective Laser Melting (SLM) and the second method is Laser Engineered Net Shaping (LENS) [19,24]. All the research conducted throughout the globe is classified into two major categories such as medical applications and structural applications. Figure 3 shows the contribution of SLM and LENS methods in above-mentioned fields.

![Figure 3. Usage of LENS and SLM process in practical research.](image_url)

In the LENS method, the contribution to the medical and structural are equal i.e each category is shared 50%. The features like flexibility in manufacturing, design and ability to handle various SMA is the key points for LENS to shine in all fields as shown in figure 4.
In the SLM method, the contribution to the medical field is more compared to the structural application [5,8,9,11,12]. Because in the structural application the phase present in SMA is very important. Since the heat produced by the laser is more so this alters the microstructure of the SMA. It is possible to alter the microstructure using heat treatment after the fabrication of SMA. For medical application, biocompatibility is first and foremost compared to strength. So, a defect-free structure like free from contamination and foreign must expected in the fabricated components (refer figure 4). The LENS and SLM process is manufacturing the components at controlled atmosphere. So, defects free components are fabricated for expected application.

![Diagram](image)

**Figure 4.** Contribution of LENS and SLM for structural and medical applications.

3. Conclusion
In order to produce the structural aerospace components and medical implants, ASTM F 167 specification recommends that the oxygen impurity levels must be kept below 300 ppm. Hence the above-mentioned procedures should be performed under a protective environment and with minimal interaction with external contaminants [33].

- In connection with the above-mentioned rules, the laser equipment will be the best choice for manufacturing SMA. Creating the controlled atmosphere to avoid contamination is possible and easy with lasers
- The suitability of automation and interface with software programmes like CAD is also helping the lasers to manufacture SMA perfectly.
- The altering of the microstructure is possible with providing suitable heat treatment to the SMA samples.
- The porous structure made by LASER is implemented for biomedical application and its shown the positive results.

All these points are encouraging the SMA (Ni-Ti) application in various fields and increase the productivity of SMA according to their need.

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