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Tensile strength of Nitinol flanges fabricated by laser rod end melting and immediate flange processing

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Abstract

Nitinol is a shape memory alloy used for actuator applications. However, the connection between Nitinol wire and mechanical system via adhesive bonding or crimping could be weakened due to the exposure of joint in aggressive environments and temperature changes. Therefore, a process chain called laser rod end melting with immediate flange processing has been put forward and proven to fabricate all-in-one Nitinol flanges. According to previous work, there is a partially solidified preform connecting to the wire as the shaft, where the connection factures under tensile tests. In the present study, the effect of size of partially solidified preform on the tensile behavior was investigated on the cylindrical flanges with different flange heights. The results show that the partial preform volume increases with the flange heights, while the tensile strength becomes smaller when the flange height is too small. This suggests that it is important to maintain the mechanical strength of Nitinol flange by choosing the appropriate flange height.

Keywords: Shape memory alloy, Laser rod end melting, Flange processing, Tensile strength

1 Contents

Nowadays, Nitinol (shape memory alloy) wires are used as actuators to conduct mechanical actions with temperature changes or heated with electrical current, widely applied in medical, automobile and aerospace industries. At present the solution of attachment to mechanical systems are mostly crimping, screwing [1] and adhesive bonding [2]. However, the adhesive bonding may have a weakened chemical and thermal resistance when the joint is exposed to aggressive environment such as chemical solution and cyclic temperature change. Thus, a robust method to fabricate all-in-one flanges is required to fulfill this application condition. Here, a so-called laser rod end melting process serve as a solution. This process is a thermal process that generates material accumulation called melt and preform (before and after complete solidification) at the end of a wire, followed by die forming or rotary swaging leading to final geometry. This process has been successfully applied to fabricate micro flange from stainless steel [3].

However, cold forming ability of Nitinol is limited because of ductility limitation and work-hardening [4]. Regarding this, the authors have developed a new approach of flange processing [5], showing that it is possible to produce chemically and thermally resistant Nitinol flanges. The fabricated flange shows a partially solidified preform connected to the wire and a newly distributed zone. Instead of the flange processing, the laser rod melting determines the microstructure distribution crossing fusion line where grain size varies and the wire-flange connection fractures under loading. In addition, the heat-treated Nitinol flange shows an improved tensile strength due to generation of metastable precipitates, indicating that the microstructure is one of factors determining the tensile behavior. In this work, it is aimed to fabricate cylindrical Nitinol flange with different heights, and the factors affecting the tensile behavior will be investigated by comparing microstructure distribution and fracture surface topography.

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2 Methodology

Fig. 1 shows the processing system for fabrication of Nitinol cylindrical flange. The chemical composition is listed in Tab. 1. The whole process is conducted in a semi-sealed chamber with the constant input of argon gas. The wire end is melted by a moving laser beam into an accumulated melt, until it reaches the upper die with a comparable volume of the lower die cavity. The laser works in a continuous-wave mode and has a wavelength of 1070 nm. During the flange processing, a pneumatic cylinder pushes the lower die upwards to reshape the melt, after a specific delay time from the start of laser melting. Assuming that the surface temperature of the melt represents its average temperature, the delay time is calculated according to the temperature-time course measured by a quotient camera and the time sequence in Fig. 1.

Tab. 1: Chemical composition of used Nitinol wire according to ASTM 2063-18

composition	Ni	C	O	Fe	Ti
wt%	56.15	0.009	0.0176	<0.01	remain

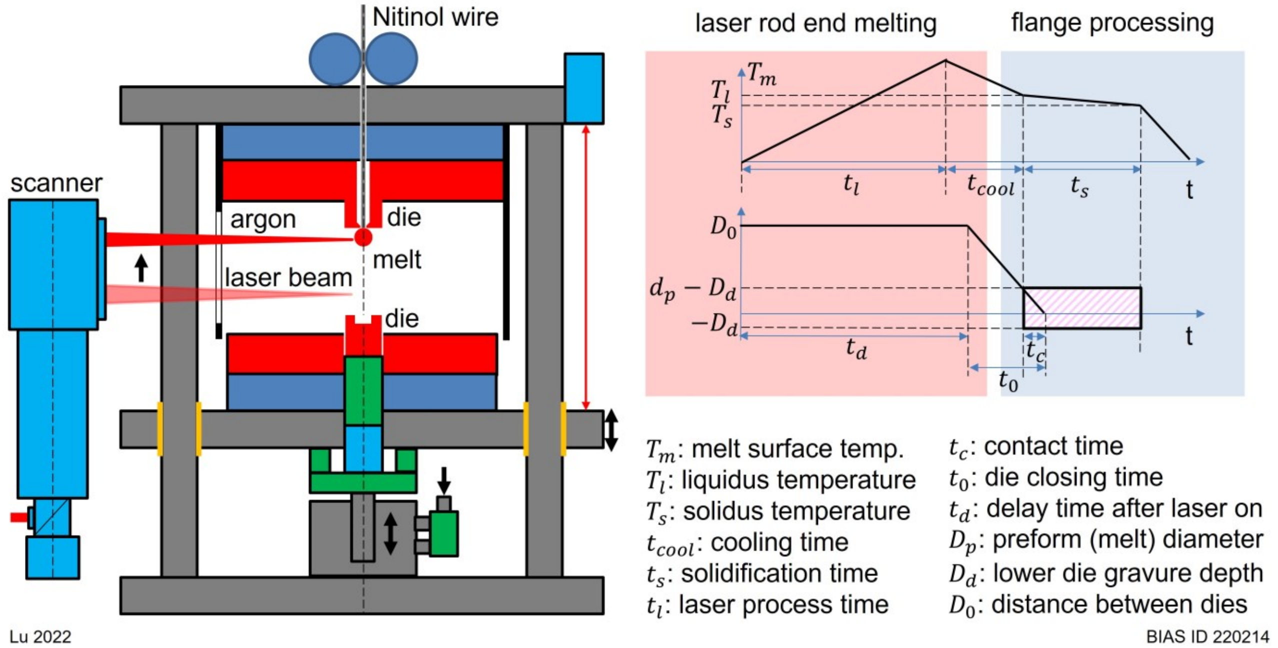

Fig. 1: Experimental setup for laser rod end melting and flange processing of Nitinol wire and their working sequence

The used lower die has a tunable bottom, so that different volume of die cavity can be set by varying its depth. Based on this the flanges with different heights can be fabricated. Correspondingly the wires with different lengths are molten, and these flanges are fabricated with the cavity depth of 0.2, 0.4 and 0.6 mm and cavity diameter of 3 mm. It has to be mentioned that the reproducibility of flange using cavity depth of 0.2 mm is quite low. In this work, the laser and flange processing parameters for flange fabrication are listed in Tab. 2, and flanges with different heights are fabricated multiple times. Afterwards, tensile tests are conducted on the fabricated flanges in a universal test machine with a constant strain rate of 0.0067 1/s. Moreover, the surface quality and microstructure of fabricated flanges are analyzed with an optical microscope and metallographic preparation by Kroll solution (93 mL H_2O, 5 mL HNO_3 and 2 mL HF, etched for 2 mins). The fractography of tested flanges is analyzed by a confocal microscope.

Tab. 2: Laser and flange processing parameters for fabrication of Nitinol flanges

laser power [W]	scan speed [mm/s]	spot diameter [µm]	die speed [mm/s]	die temperature [°C]
85	5	55	48	20

3 Results

Fig. 2 shows the successful fabrication of cylindrical Nitinol flanges with different heights. The surface appears reflective without evident oxide layer. Fig. 3 show the comparison between the geometry and microstructure of flange. For the flange size, the flange height is generally larger than the die cavity depth. Inside the flange, there are three typical zones: heat affected zone (Zone A), partially solidified preform (Zone B) and newly distributed Zone C. The grain size varies from Zone A to Zone C and the grains of both fusion zones orient towards each other. The solidification front in Zone C is always found in the center, and it coincides with the boundary between Zone B and Zone C partially. With decreasing die cavity depth, the flange height and thickness of Zone B becomes smaller.

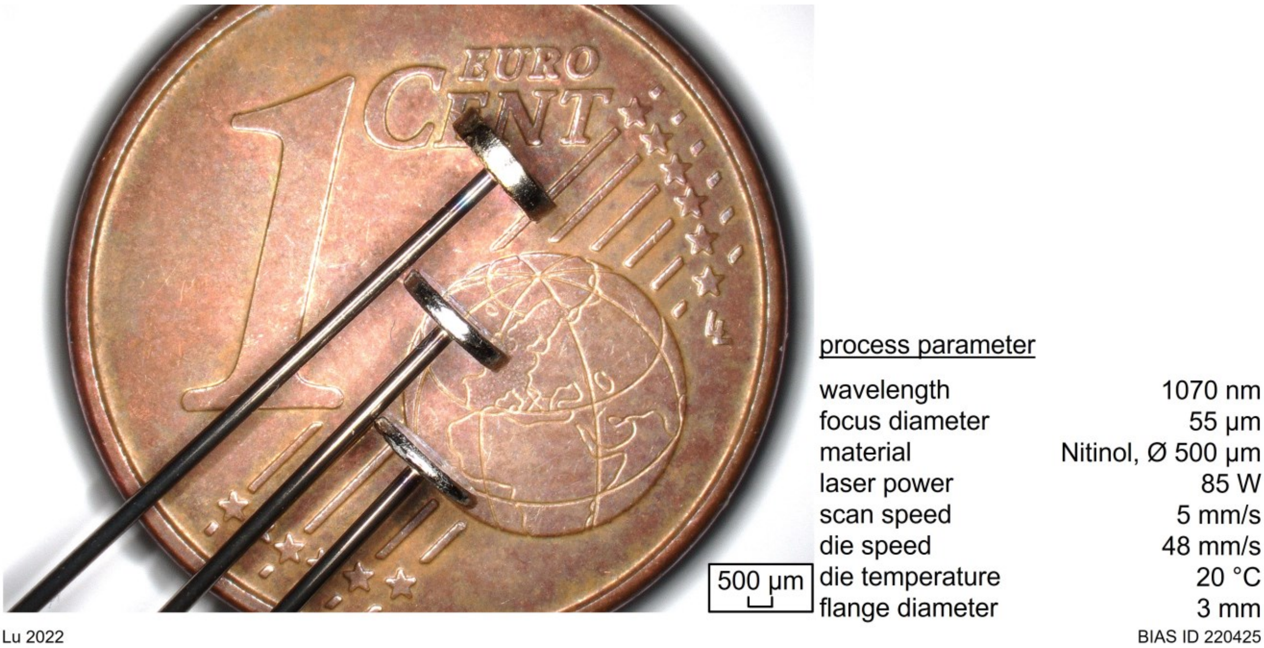

Fig. 2: Nitinol flanges with cylindrical shape

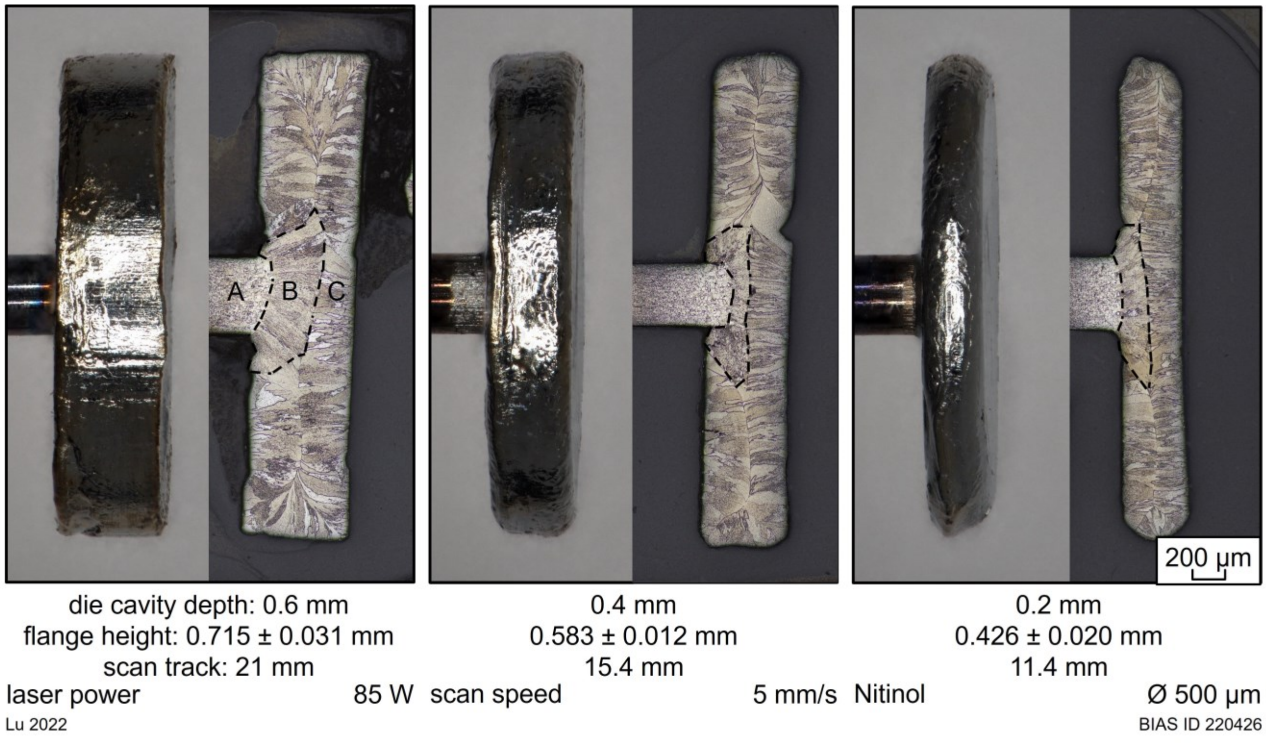

Fig. 3: Surface quality and microstructure distribution of the cylindrical Nitinol flanges with different flange heights

Fig. 4 shows the tensile behavior and fracture results of flanges in Fig. 3, and the maximum of height map scale in the fracture surface topography stands for the base surface of flange. The tensile test of original wire is based on the previous work. Each strain stress curve is made of average value and standard deviation from the multiple tests. In general, curves of flanges and wires overlap each other. The curve of wire shows a typical loading stress plateau with increasing strain. In comparison, flanges with average heights of 513 µm and 715 µm fracture in the loading plateau, while the flanges for 426 µm fracture before entering this phase. The corresponding fracture topographies show that material at the connection between the flange and wire is pulled out, and the maximum fracture depth increases with the flange height. In addition, the fractured wires and flanges are comparable.

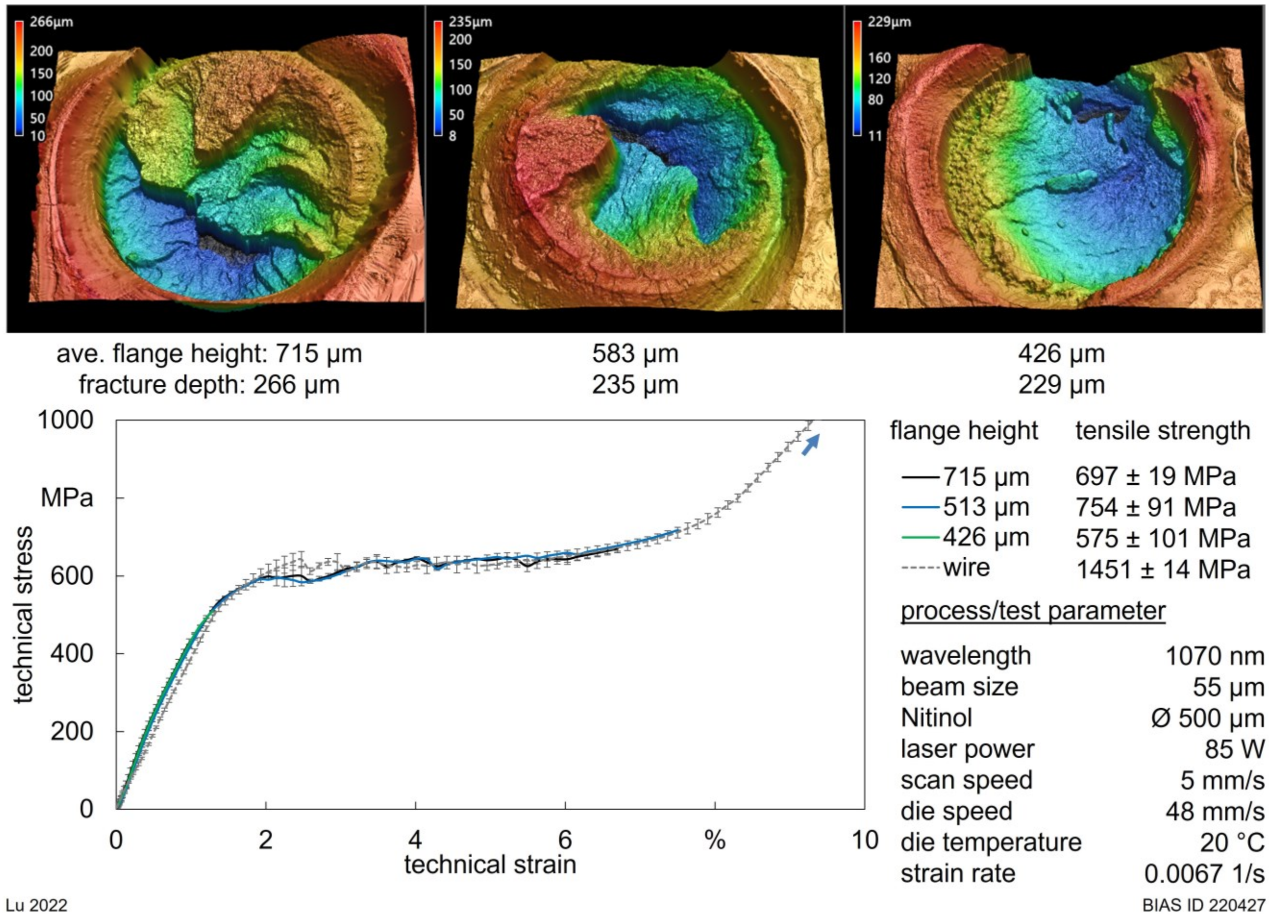

Fig. 4: Tensile tests of cylindrical Nitinol flanges with different flange heights and corresponding fracture surface topography in height map

4 Discussion

By comparing with previous work, in this study it shows that the laser rod end melting and flange processing enables the fabrication of cylindrical Nitinol flange besides the truncated cone shaped one. Despite of the flange shape, the partially solidified preform and newly distributed zone are always generated in the flange. With decreasing flange size, the former zone becomes smaller (cf. Fig. 3). By comparing the axial size of partially solidified preform (Zone B) and fracture height map (see Fig. 4), it shows that the flanges with height of 513 µm and 715 µm fracture inside Zone B (see Fig. 3) while this zone in the flange with height of 426 µm is almost pulled out. This corresponds to its lower tensile strength, indicating that the boundary between the partially solidified preform (Zone B) and newly distributed zone is a weaker zone compared to the heat affected zone in wire and wire-flange connection [5]. Nevertheless, this phenomenon can be avoided by the larger partially solidified preform. One reason might be explained by the wedge-shaped newly distributed zone preventing from the pull-out of partial preform. In addition, the tensile strength between cylindrical flanges with height of 513 µm and 715 µm and the truncated cone shaped ones from previous work are comparable.

5 Conclusions

The following conclusions can be drawn based on the investigation:

- Laser rod end melting and flange processing in a not fully solidified state enable the fabrication of Nitinol flange with cylindrical shape.
- The boundary between the partially solidified preform (Zone B) and newly distributed zone inside the flange is a weak point, and too small former zone leads to its fracture under lower tensile stress. Therefore, miniaturization of Nitinol flange while maintaining its mechanical strength is achieved by choosing the appropriate flange size.

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