Heat affected zone analysis for laser and micro-electrical discharge machined nitinol

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Abstract
As the demands for implantable nitinol micro-devices proliferate, so does the need for improvements in strength, fatigue, radiopacity and biocompatibility. Heat-affected zone (HAZ) is a really critical factor in thermal processes as it directly influences the need for finishing processes depending on the intended application. Finishing processes like electropolishing and buffing are expensive hence increasing the cost of production. For nitinol, the HAZ could affect shape memory and/or superelasticity and ultimately part performance. Even though micro-electrical discharge machining (µEDM) and Laser cutting are both thermal processes, their nature of ablation is dissimilar, and so are the involved performance control parameters. Owing to its higher material removal rate, laser cutting has been more predominantly used to machine nitinol but as the demand for better surface finish and closer dimensional tolerances increases, this advantage could be negated and thereby favoring µEDM. This study analyses both the surface and subsurface of nitinol tubes machined by µEDM and laser cutting and reports on the effect of varying open circuit voltage on the size and distribution of the heat-affected zone in µEDM. This is then compared to HAZ from laser-cut surfaces with an aim of making a case for µEDM as a suitable standalone process for manufacturing nitinol medical micro-parts.
Key words: nitinol, heat-affected zone, µEDM, laser cutting

Introduction
Owing to the intensive thermal flux involved in µEDM and laser cutting, a recast layer and HAZ are formed. For conventional EDM, the HAZ could range from a few hundred microns for roughing operations to a few microns for finishing operations [1]. For µEDM however, the HAZ is significantly reduced owing to the smaller discharge energies (0.0005 – 0.5 mJ) [2]. The HAZ in both processes have, not only different composition from the bulk material as they have smaller submicron grains [3], but are also dissimilar from one process to the other. HAZ in µEDM is not uniformly distributed on the surface and has a higher nanohardness than the bulk whereas the HAZ in laser cutting is uniformly distributed and with a lower nanohardness than bulk material [3]. This zone needs to be completely removed or minimized as it can alter part performance. As opposed to µEDM which uses a series of electrical sparks to result in material removal, laser cutting uses highly focused monochromatic, coherent and collimated light beams, assisted with a jet of gas or water under controlled pressure to cut through material. Table 1 compares the two processes.

Table 1: Comparison between µEDM and Laser cutting [2], [4], [5]

Process	Accuracy	MRR	Application	Surface finish
µEDM	±0.0025mm	0.0005 – 0.03 mm³/min	Limited to conductive materials	$R_a \geq 0.1$ µm
Laser cutting	±0.025 mm	5-10 times faster	Limited to non-reflective materials	Ra ≥ 0.2 µm

Methodology
In order to analyze the HAZ characteristics, grooves with an average length of 5 mm were cut on nitinol tubes with an outer diameter (OD) of 6 mm and a thickness of 0.5 mm using µEDM and Laser. For the µEDMed samples, a Sarix-SX100 high precision machine was used whereby the discharge energy setting (CF) was maintained at CF100 and the open circuit voltage varied from 60V to 200V. Typical values for actual discharge energies from these settings are shown in Table 2.

Table 2: Actual discharge energies for Sarix SX100 CF100 energy level setting

Voltage, V	60	80	100	120	140	160	180	200
Energy, µJ	0.95	1.69	2.64	3.80	5.17	6.76	8.55	10.56

For the Laser cut samples, a water guided Fiber Laser System 200W machine with a cutting kerf of 20 – 50 µm was used. After machining, the grooves were then prepared for HAZ analysis by carefully controlled grinding and polishing of the machined surface. Afterwards, a color etching technique produces selective contrasts based on factors including different grain orientations and grain boundaries. Selected samples were further analyzed using electron backscatter diffraction (EBSD) method for confirmation purposes.

Results and Discussion

Samples machined using µEDM had no visible HAZ while those from laser cutting had a uniformly distributed HAZ along the cut edges with a width ranging from 9-13 µm. The lack of a visible HAZ on the µEDMed sample surfaces were due to the low discharge energies involved (0.95µJ – 10.56 µJ). On the contrary, the high power laser beams subjected to the laser cut samples explain the presence of a significant HAZ.

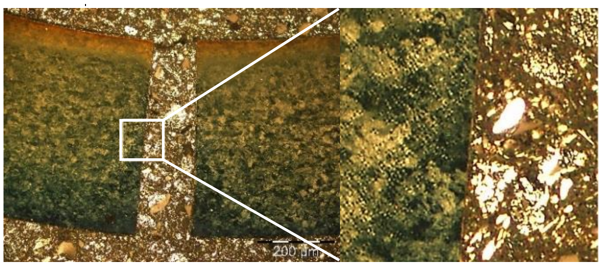

Figure 1: µEDM sample (CF100, 200V)

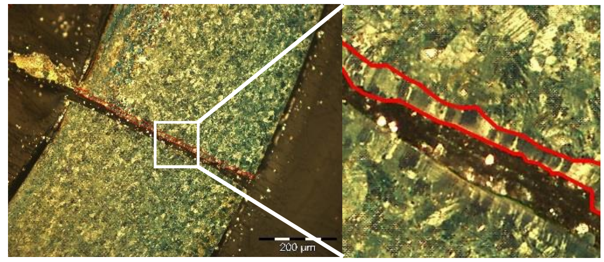

Figure 2: Laser cut sample with HAZ (red marked area)

In order to investigate their validity, the results obtained were compared to those realized from µEDM of high aspect ratio steel bores. As shown in Table 3, machining using parameters equivalent to CF100 did not generate a detectable HAZ showing consistency in the results. Also revealed in Table 3 is that an increase in discharge energy results in an increase in the HAZ.

Table 3: HAZ values for µEDMed high aspect steel bores

Discharge energy [µJ]	Voltage, [V]	HAZ, [µm]
3.80	120	0.0
16.6	160	1.5
48.04	160	2.1
124.39	160	2.9

From the experiments undertaken, MRR values ranged between 0.005-0.025 mm³/min. Though this is inferior to that of laser cutting, µEDM's superiority with regards to having a lower HAZ make the process suitable for processes for which reduction in HAZ is the most important performance measure.

Conclusions

From this research, it is clear that µEDM presents clear advantages as far as the size of HAZ is concerned as the µEDM samples analyzed did not reveal a HAZ as opposed to laser cut samples which have a HAZ ranging from 9 – 13 µm. Since Laser cutting offers a higher MRR, further analysis of costs associated with removing this unwanted HAZ coupled with optimization of the µEDM process is necessary so as to give an insight on its commercial viability.

Acknowledgements

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