Applied Surface Science 353 (2015) 291–299

Contents lists available at ScienceDirect

Applied Surface Science

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

Statistical characteristics of surface integrity by fiber laser cutting of Nitinol vascular stents

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ARTICLE INFO

Article history:
Received 12 May 2015
Accepted 18 June 2015
Available online 26 June 2015

Keywords:
Surface integrity
Cardiovascular stent
Fiber laser cutting
Effect size
Shape memory alloy

ABSTRACT

Nitinol alloys have been widely used in manufacturing of vascular stents due to the outstanding properties such as superelasticity, shape memory, and superior biocompatibility. Laser cutting is the dominant process for manufacturing Nitinol stents. Conventional laser cutting usually produces unsatisfactory surface integrity which has a significant detrimental impact on stent performance. Emerging as a competitive process, fiber laser with high beam quality is expected to produce much less thermal damage such as striation, dross, heat affected zone (HAZ), and recast layer. To understand the process capability of fiber laser cutting of Nitinol alloy, a design-of-experiment based laser cutting experiment was performed. The kerf geometry, roughness, topography, microstructure, and hardness were studied to better understand the nature of the HAZ and recast layer in fiber laser cutting. Moreover, effect size analysis was conducted to investigate the relationship between surface integrity and process parameters.

1. Introduction

1.1. Nitinol material

Nitinol is a binary nickel–titanium alloy of near equiatomic composition. It is well known for its outstanding properties–namely superelasticity, shape memory, and biocompatibility. Superelasticity means Nitinol can have a wider elastic region (up to 8%) compared to conventional materials such as stainless steel. Shape memory describes the process in which Nitinol returns to its previously defined shape when heated above the transition temperature. The basis for superelasticity and shape memory in Nitinol is a temperature and/or stress induced martensitic phase transformation process as opposed to the conventional diffusion induced transformations. The reversible solid state crystalline phase transformation occurs between a high symmetry parent phase (austenite) and a low symmetry product phase (martensite). Nitinol austenite is a B2 (cubic) type ordered structure and Nitinol martensite is a monoclinic distortion of a B19 lattice. When Nitinol is in martensite phase, it has the special ability to undergo certain amount of plastic deformation without causing slip. This process of plasticity is called twinning, which involves a shift of atoms on one side of a twinning plane to form a mirror image of atoms on the other side of the twinning plane. Guo et al. [1] summarized the stress–strain–temperature diagram to illustrate the superelasticity and shape memory process of Nitinol alloys based on the phase transformation process.

1.2. Stent application and laser cutting process

Due to superelasticity and superior biocompatibility, Nitinol has received considerable attention in biomedical applications. One of the typical examples is cardiovascular stents. A stent is a cylindrical medical device used to widen a narrow or stenosed lumen in order to maintain the patency of the lumen [2]. By far, the vast majority of coronary stents are produced by laser cutting from tubes [3]. The common setup of the laser cutting process uses a laser beam passing through coaxial gas jet structure to focus on the working surface of the tube as the linear and rotary velocity of the tube is precisely controlled [4]. In this setup, the laser is mounted on translation/rotation system. The system moves the tube with respect to the laser beam in order to cut the tube into the desired structure.

1.3. Research objectives

Fiber laser cutting is an emerging process for cutting Nitinol. Compared to a conventional Nd:YAG laser, fiber lasers have advantages such as better beam quality, reliability, and process efficiency

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http://dx.doi.org/10.1016/j.apsusc.2015.06.105
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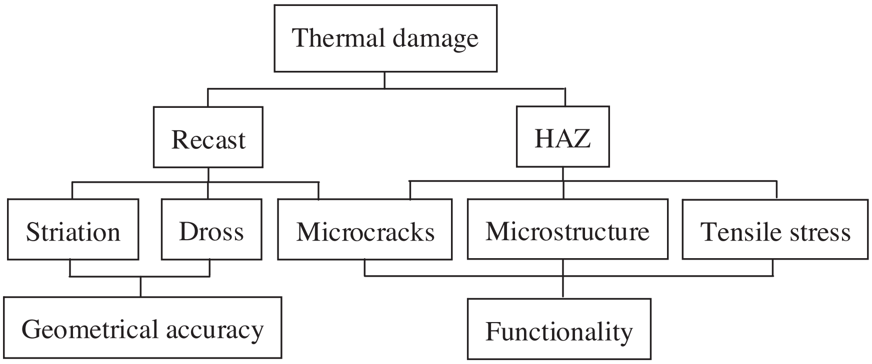

Fig. 1. Thermal damage definition in laser cutting and its relationship to part performance.

with lower acquisition cost and maintenance. Therefore, fiber laser cutting Nitinol has great potential to manufacture high quality stents. However, fiber laser cutting is a thermal process, which results in thermal damage such as striation, dross, recast layer, HAZ, microcracks, and tensile residual stress. The striation increases the roughness of the kerf. Dross and recast layer lead to non-uniform kerf profiles. Recast layer, HAZ, and microcracks alter the microstructures in the subsurface, which consequently reduce the tensile and fatigue performance of the material. A detailed definition of thermal damage from laser cutting and its relationship to part performance can be found in Fig. 1. Currently, little research has been done to investigate surface integrity and thermal damage characteristics of fiber laser cutting Nitinol. The process capability of the fiber laser cutting on Nitinol from the statistical perspective is still to be investigated. Moreover, a general guideline for selecting process parameters to optimize surface integrity is highly necessary.

To solve these pressing issues, the objectives of this study are to: (1) investigate the effect of key process parameters on surface integrity of fiber laser cutting Nitinol, (2) understand the nature of HAZ and recast layer by microstructural analysis and nanoindentation, and (3) evaluate the process capability with statistical analysis.

2. Background on surface integrity by laser cutting of Nitinol

Since the first laser cutting system in the mid-1960s, more and more attention has been put into laser cutting technology due to its wide range of applications and its remarkable cutting capability. Different types of lasers used in material processing include carbon dioxide (CO_2) lasers, neodymium-doped yttrium aluminum garnet (Nd:YAG) lasers, fiber lasers, excimer lasers, and ultra-short pulse lasers [5]. For laser cutting and micromachining, Nd:YAG, fiber, and ultra-short pulse lasers are most commonly used.

Depending on the laser pulse range, laser types can be categorized in to long pulse lasers (pulse width > 10 ps) and ultra-short pulse lasers (pulse width < 10 ps) [6]. The laser cutting mechanisms for long pulse and ultra-short pulse lasers are fundamentally different.

The fundamental mechanism of long pulse laser cutting is thermal heating (absorption and conduction), dynamic melting, and/or evaporating (phase transition and material removal) of the base material in the cut kerf [7]. An assisting gas jet is used to expel the molten material away from the kerf. Molten and vaporized material re-solidifies to form recast and dross. The diffused heat into the vicinity of the cut zone creates a heat affected zone (HAZ). The HAZ formation typically leads to strain coarsening, which degrades the material strength. In addition, microcracks are often formed by laser induced thermal stress [8]. The thermal induced tensile stress is also known to detrimentally affect the fatigue performance of the final parts. Due to the thermal damage, post-processing is often used to remove thermal damage and enhance part performance. For example, electropolishing is one of the most widely used post-processing techniques in stent manufacturing process chain. This process is found to be not only increase the fatigue performance [9] but also the corrosion performance [10]. Post-processes are essential for better quality of final products. However, post-processes need to be conservatively used because (1) they are high cost and time consuming, (2) most of the post-processing procedures involves the use of hazardous chemicals, and thus can potentially contaminate the final product, and (3) they can detrimentally affect the final products, even cause failure of the component.

For ultra-short pulse lasers, the femtosecond pulse duration can enable very high laser intensity, e.g. 10^{15} W/cm^2 by Liu et al. [11]. At this high intensity, the electric field is sufficiently high to induce non-linear effect, i.e. multiphoton absorption [11,12] and vaporize material within a very small amount of time. The direct phase transition of the materials to vapor state produces extremely high cut quality with smooth surfaces and clean cuts. The HAZ can be minimized since thermal diffusion time is strongly limited by the ultra-short pulse. Obviously, ultra-short pulse lasers opened new possibilities for stent manufacturing. However, due to the low material removal rate, high acquisition cost and high maintenance, the stent manufacturing using ultra-short pulse lasers is not yet well commercialized in industry.

Due to the different material removal mechanisms of long and ultra-short pulse lasers, the resultant surface integrity is significantly different. Important features such as cutting geometry, surface finish, HAZ, recast layer, and residual stress can be greatly affected by laser cutting process parameters.

2.1. Nd:YAG laser cutting Nitinol

In most laser cutting applications, the desired cutting geometry is critical for better product performance. For instance, in stent applications, straight edges with desired taper angle will lead to uniform fluid flow in the blood vessel. Geometrical attributes that need to be considered after laser cutting are (1) kerf width (both for entry and exit), (2) taper angle, and (3) kerf deviation.

In Nd:YAG laser cutting Nitinol, kerf width generally increases with increasing pulse energy and decreasing cutting speed due to higher energy accumulation [13,14]. Increasing pulse width results in a bigger taper angle [13] and a negative laser beam offset decreases the taper angle [14].

Periodic lines usually appear on laser cut surfaces, also known as striations. These affect the roughness and precision of laser cut parts. For Nitinol alloys, with assisting gas, high repetition rate produces better surface quality due to high pulse overlapping [15]. Pfeifer et al. [13] found that minimum roughness was achieved