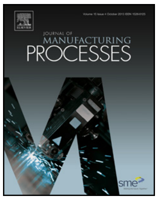
Journal of Manufacturing Processes 19 (2015) 81–86

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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



Technical Paper

Finite element simulation and experimental validation of pulsed laser cutting of nitinol

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ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form 1 May 2015
Accepted 1 May 2015
Available online 12 June 2015

Keywords:
NiTi
Shape memory alloy
Laser cutting
FEA
Surface integrity

ABSTRACT

Nitinol (NiTi) alloys are widely used in laser cutting of cardiovascular stents due to excellent biomechanical properties. However, laser cutting induces thermal damage, such as heat affected zone (HAZ), micro-cracks, and tensile residual stress, which detrimentally affect product performance. The key process features such as temperature distribution, stress development, and HAZ formation are difficult to measure experimentally due to the highly transient nature. In this study, a design-of-experiment (DOE) based 3-dimensional (3D) finite element simulation was developed to shed light on process mechanisms of laser cutting NiTi. The effects of cutting speed, peak pulse power, and pulse width on kerf width, temperature, stress, and HAZ were investigated. A DFLUX user subroutine was developed to model a moving volumetric (3D) heat flux of a pulsed laser. Also, a material user subroutine was used that incorporated superelasticity and shape memory of NiTi.

1. Introduction

Nitinol (NiTi), a nickel–titanium alloy of near equiatomic composition, is well known for its outstanding properties such as superelasticity, shape memory, and good biocompatibility. Superelasticity means NiTi can have a wider elastic region (up to 8%) compared to conventional materials such as stainless steel. Shape memory describes the process in which NiTi returns to its previously defined shape when heated above the transition temperature. Both of these properties are based on a phase transformation process. There are two common phases at room temperature that are involved in the phase transformation process: (1) martensite, which is stable at lower temperatures and (2) austenite, which is stable at higher temperatures. The austenite to martensite transformation can be triggered by applying stress or thermal loading [1].

Due to the excellent biomechanical properties, NiTi has received considerable attention since its discovery in 1962 at the Naval Ordnance Laboratory. The excellent biomechanical properties refer to similar mechanical behavior to human tissue, good biocompatibility, and non-toxicity. Many of the early applications of NiTi focused on the shape memory effect. In recent years, a lot of attention has been aimed toward the superelasticity of NiTi, with particular emphasis on biomedical applications [2]. A typical example 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. Currently, stents are being increasingly used in blood vessels and gastrointestinal, renal, and biliary tracts [3]. There are many materials such as stainless steel, cobalt-chromium, and NiTi alloys used in making stents. NiTi is preferred because of its flexibility and ability to maintain shape in a curved lumen. Moreover, the non-linear mechanical response of NiTi is similar to natural material, such as hair, bone, and tendon.

The manufacturing process for stents is very complex. Traditionally, machining is done by laser cutting due to the stent's complex geometry and NiTi's poor machinability. Stoeckel et al. [4] reported that approximately half of the manufacturers use laser cutting for self-expanding NiTi stents. A common setup for laser cutting is to use a finely focused Nd:YAG laser beam that passes through a coaxial gas jet to impinge the working surface of the tube while the linear and rotary velocity of the tube is precisely controlled [5].

There have been numerous studies aimed at understanding laser cutting of NiTi. However, due to the uniqueness of the NiTi material, the process mechanisms are poorly understood. Therefore, the objective of this study is to develop a finite element simulation of laser cutting NiTi to shed light on: (1) kerf width prediction and validation, (2) temperature distribution, (3) stress distribution, and (4) HAZ prediction at different cutting conditions.

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http://dx.doi.org/10.1016/j.jmapro.2015.06.005
1526-6125/

2. Heat flux modeling in laser cutting

Important process features in laser cutting such as temperature distribution, stress propagation, and HAZ formation are directly related to cutting quality. However, they are difficult to measure experimentally since laser cutting is a highly transient process. Therefore, finite element simulation was used intensively to gain insight into the process. Simulations have been used to aid in determining accurate thermal loading, verifying experimental data, and predicting temperature and residual stress profiles.

An accurate thermal model is critical to simulate the laser cutting process. The most commonly used heat flux model has the form of

$$I = \frac{AP}{\pi r_0^2} \exp\left[-B\left(\frac{r}{r_0}\right)^2\right] \tag{1}$$

where I is the laser intensity, A is the laser absorption coefficient, P is the laser power, r_0 is the spot radius, B is the shape factor of the Gaussian distributed heat flux, and r is the distance to beam center.

Different geometrical shapes of heat flux were explored by many researchers [6–12]. It was shown that a volumetric (3D) heat flux has advantages over a surface (2D) heat flux in predicting the thermal response of the material during laser processing. Therefore, researchers proposed different forms of volumetric heat flux to simulate laser processing in different applications. Yilbas et al. [7] simulated laser cutting of thick sheet metal using a volumetric thermal model. The stress field and temperature field were predicted and found to be in agreement with experimental observation. Shuja et al. [10] used a similar volumetric heat flux to simulate laser heating of a moving slab. It was found that predicted melt thickness agreed with experimental measurements. Lacki and Adamus [6] stated that the advantage of a conical volumetric heat flux versus a surface heat flux was that it better captured the shape of the thermal field in deep welds during laser melting. Luo et al. [11,12] found that the use of a conical shape heat flux better simulated the laser–material interaction with high penetration depth.

Pulsed laser operation is a key feature for current laser cutting processes. Different pulse durations and repetition rates significantly affect surface roughness [13,14] and residual stress [15]. Therefore, it is critical to incorporate the pulsed laser operation in modeling of heat flux. A simulation using a 3D moving heat flux in pulsed mode on NiTi is essential to improve the fundamental understanding of process mechanisms and the influence of process parameters.

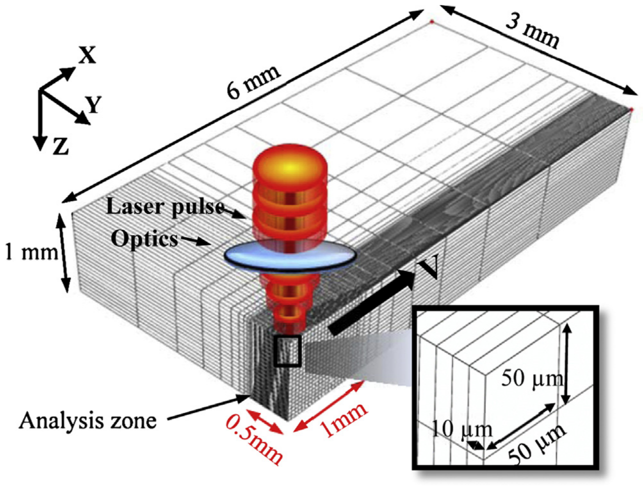

Fig. 1. Simulation schematic of pulsed laser cutting.

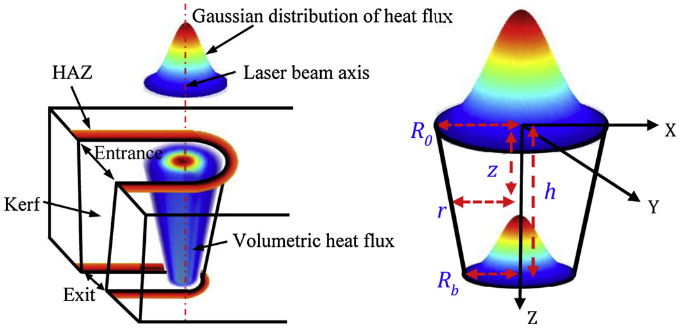

Fig. 2. (a) Schematic of laser cutting; (b) conical shaped volumetric heat flux.

3. Simulation procedure

3.1. Mesh

The mesh design is shown in Fig. 1. The dimensions of the workpiece were 6 mm (length) × 3 mm (width) × 1 mm (thickness). The laser cutting direction was along the X-axis. Element size was biased with a higher density of elements along the cutting direction (X-axis). Within the fine mesh in the analysis zone, the element size was 50 μm × 50 μm × 10 μm. The boundary condition on the bottom plane is fixed to provide proper constraint of the workpiece. Also, the model is symmetric with respect to X–Z plane so that only half of the workpiece needs to be modeled to decrease the computational time. The initial temperature was room temperature (20 °C).

The simulation was performed using Abaqus/Standard since the moving heat flux subroutine DFLUX can only be programed with the implicit solver. The advantage of using the implicit solver was that the temporal discretization was more stable despite a certain reduction in computational efficiency. In order to determine the temperature and stress distribution after laser cutting, a coupled thermal–mechanical analysis was used. The laser cutting process was based on 3D transient heat transfer. The criterion to model material removal was based on whether nodal temperature exceeds the melting temperature.

3.2. Modeling of moving volumetric (3D) heat flux of pulsed laser

In order to understand the laser cutting process from a theoretical perspective, a schematic of 3D heat flux is shown in Fig. 2(a). The conical shape volumetric heat flux moves along the workpiece to generate a cutting kerf and form a heat affected zone (HAZ) on both entrance and exit sides of the kerf.

To simulate the characteristics of the heat flux of laser pulses, a DFLUX user subroutine of conical shape volumetric heat flux was developed. The subroutine featured (1) a moving Gaussian heat flux from laser, (2) a pulsed operation, and (3) a conical volumetric (3D) heat flux. The output of the subroutine was the heat flux given by the following equation:

$$F = \frac{CP}{\pi {R_0}^2 h} e^{(-3(x^2+y^2)/r^2)} \theta(f, \tau) \tag{2}$$

where F is the applied heat flux, C is the energy absorption coefficient, P is the peak pulse power, R_0 is the laser spot radius on the top surface, h is the sample thickness, f is the laser frequency, τ is the pulse width, and r is the instantaneous radius of the heat flux, which for a conical shape is given by

$$r = R_0 - (R_0 - R_b) \times \frac{z}{h} \tag{3}$$