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Effects analysis of ambient conditions on process of laser surface melting

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ABSTRACT

In the process of laser surface melting (LSM), ambient conditions around the workpiece have important influences on the processing results. As an effective and feasible method for ambient changing, water-assisted approach can be expected to gain better results such as desired machining goals and reliable service performances. However, the effects of different water ambient on LSM process are needed to be further clarified. To this end, three 3-D transient process models in ambient dry air, water film and water are developed, respectively, using finite element method (FEM); the thermo-mechanical parameters, which depend on temperature, are taken into account and the complex physical essences are integrated. In experimental verification, these three LSM processes on mild steel Q235 are carried on and the computed results are in good agreement with respective measurements. Based on the proposed models, the transient temperature fields and residual stress distributions on workpieces are investigated. The numerical results suggest that the states of temperature and residual stress fields can be improved to different degrees using water film and water ambient.

1. Introduction

Laser surface melting (LSM) is a flexible surface treatment technology and now widely applied in manufacturing industry such as automobile, aerospace and power engineering [1,2]. More recently, it is crucial to improve the processing and machining qualities due to which most of these applications require higher performances including fast processing [3,4], melting layer homogeneity and refinement of grain size on metal surface, etc. [5–7].

In these enhancement efforts, water-assisted laser processing plays an important role and can be added on purpose to gain better results [8,9]. Since 1970s, laser processing in presence of liquid water has been studied, and to date, a series of investigations have been done for water-assisted processes of steam laser cleaning (SLC) [10–12], laser shock processing (LSP) [13–15] and laser cutting (LC) [16,17]. It was shown that the effect of water in these processes mainly consists of laser energy conversion, materials transport and shock waves induction, as well as cooling the workpiece more effectively and useful chemical reactions [8]. However, on the other hand, this important assisted processing is rarely studied in laser beam welding (LBW) and modifying (LBM) where LSM process presents dominantly. At early times, Kojima et al. developed under water welding with YAG laser for the repair of nuclear reactor vessels and found that the cooling rate was higher than that in TIG welding [18]. In recent works, Kumar et al. studied the CO_2 LBW of mild steel with ambient and under water medium. A significant performance is realized that laser induced keyhole is deeper and narrower under water as compared with that formed in ambient condition [19]. Effect of shielding conditions on under water LBW quality with YAG laser was investigated by Zhang et al. The experiments under various water depths were performed and the influences of shielding condition were discussed [20]. According to Guo et al., the medium effect on mechanical properties of cast iron in biomimetic coupling LSM was researched. They drew the conclusion that the application of water film played a key role in improving the friction properties and wear resistance [21]. From the reviews above, it is seen that most investigations are concentrated in under water laser processing and the thermo-mechanical performances were not analyzed enough. In addition, in order to carry the debris away more effectively in laser etching (LE), another important water-assisted processing method has been proposed by Ageev [22] and Dupont et al. [23]. For this attempt, workpiece was processed under water film generated by a nozzle, and as a result, a desired high cooling rate was attained simultaneously. Thus, reasonably, this approach can be undertaken in LSM process and the effect needs to be exhibited.

In the present work, the effects of ambient conditions on LSM process are further clarified using finite element method (FEM). Firstly, three numerical models of LSM in air, under water film and water ambient conditions on mild steel Q235 workpiece are established. Then, the temperature fields and residual stress distributions of substrate are calculated. Finally, the numerical results are analyzed to show the performances of LSM process under these ambient conditions.

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2. Numerical models

In LSM process under different ambient conditions, a moving laser beam strikes the surface of substrate and a narrow melting zone is suddenly fused and froze locally. To investigate these processes, three numerical models and the thermo-mechanical analyses are needed.

2.1. Models descriptions

The processes of LSM in air, under water film and under water are indicated in Fig. 1. Fig. 1(a) shows the general LSM in dry air as well as the substrate geometry and results measuring positions used in all cases. For water-assisted LSM in Fig. 1(b), water film was generated by a jetting nozzle with a radius of 1.5 mm, flow angle of 45° and speed of 0.3 m/s, which moved following the laser simultaneously. The distance from jetting incidence point to laser spot was set to 5 mm. As shown in Fig. 2, the water flowage area was calculated using the hydrodynamic code Fluent. In order to be induced into the calculation conveniently, the boundaries of this area were simplified and depicted by three equations.

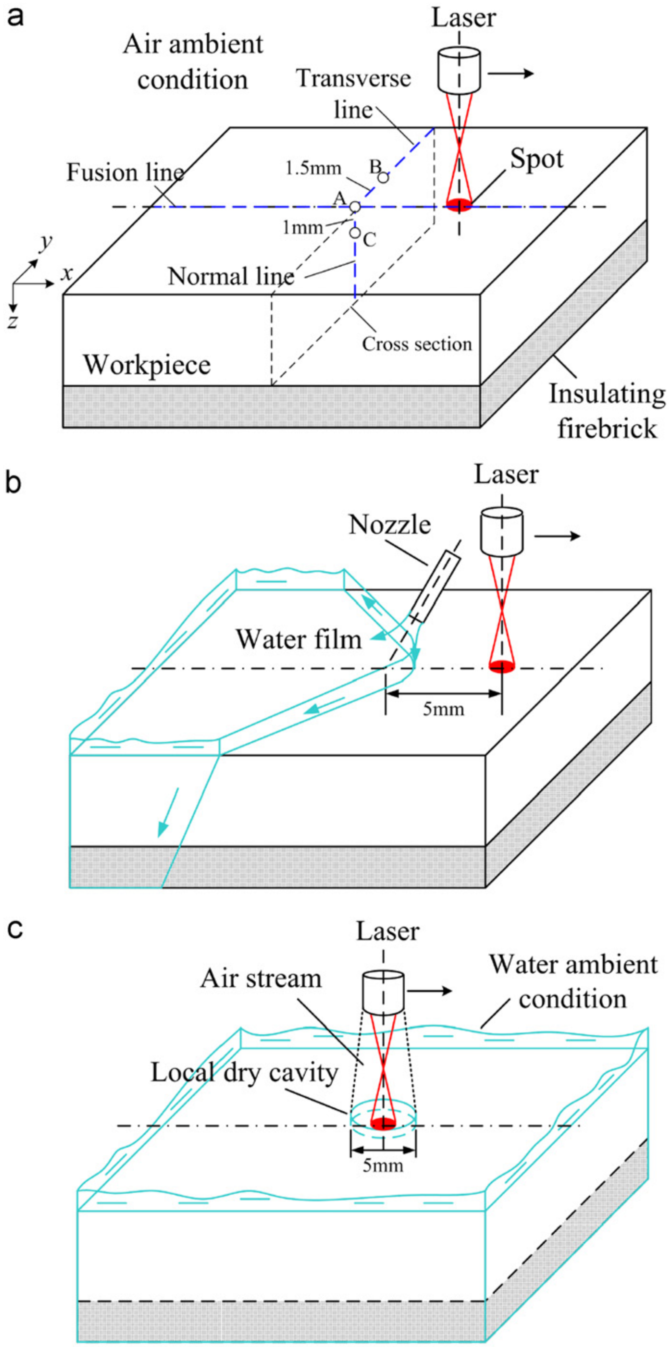

Fig. 1. Schematics of LSM process under different ambient conditions: (a) in air, (b) under water film and (c) submerged in water with local dry cavity.

Workpiece was fixed into a tub of water for under water LSM as in Fig. 1(c), such that the steel sample was kept ~2 mm below water surface. For assurance of the quality in under water laser processing, the effect of water on the metallurgical behavior should be considered [20]. In order to exclude the water around the remelting zone (RMZ), a local dry cavity on the workpiece was created approximately 5 mm in diameter by an air stream coaxial with laser beam [15].

2.2. Numerical procedure

In view of the present developments in research [6,7,24,25], useful for analysis of the LSM process, the assumptions introduced are as follows:

- The complex physical mechanisms of the keyhole formation and melting metal flow in the pool were ignored.
- The steel surface was regarded to be smooth and the material was elastic, plastic and isotropic.
- In initial state, the substrates were stress-free and a same ambient temperature was specified for all the three cases.

The 3-D numerical models are developed using the commercial FEM code ANSYS to predict the temperature and stress distributions in workpiece, specifically in the RMZ. Numerical simulation is decoupled to two steps, the temperature field result came from heat transfer analysis in the first step is used as input to the mechanical analysis, and the thermal solid elements with eight nodes Solid70 are converted to Solid45 with eight nodes for the mechanical analysis. The thermo-physics material properties are considered as dependent on temperature. As shown in Fig. 3, for the appropriate result of compromise between computing time and accuracy, a dense mesh is used around the fusion line and a coarser mesh is adopted for the rest.

2.3. Thermal analysis

A 3-D Cartesian coordinate system is established on workpiece with x-axis along the longitudinal (melting) direction, y-axis along transverse direction and z-axis along the thickness direction. The governing partial differential equation of LSM process can be written as [26]

$$\frac{\partial^2 T(x,y,z)}{\partial x^2}+\frac{\partial^2 T(x,y,z)}{\partial y^2}+\frac{\partial^2 T(x,y,z)}{\partial z^2}=\frac{1}{\alpha(T)}\frac{\partial T(x,y,z)}{\partial t} \tag{1}$$

where let $\alpha(T)=k(T)/\rho(T)\,c(T)$, which is called the thermal diffusivity; $k(T)$, $\rho(T)$ and $c(T)$ represent the thermal conductivity, density and specific heat of the material, respectively, which depend on the temperature T.

The worpkiece is placed on a refractory block and the bottom surface is kept in adiabatic condition. The surfaces of workpiece where thermal boundary conditions are carried can be shown as in Fig. 1. On the top, bottom and side surface regions (denoted by Ω_1, Ω_2 and Ω_3, respectively), the heat balance can be given as

$$\Omega_1: -k\nabla T\cdot \mathbf{n}_t=q_L-q_c \tag{2}$$

$$\Omega_2: q_L=q_c=0 \tag{3}$$

$$\Omega_3: -k\nabla T\cdot \mathbf{n}_s=-q_c \tag{4}$$