Laser Material-Removal Process as a Subject of Automatic Control

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Introduction

CNC-controlled laser machining of precision components is being used increasingly in modern industry. However, the laser machining system operator has to make a host of complex decisions, usually based on trial-and-error methods to set process control parameters. The laser-related parameters are laser power, focal position, frequency of the laser impulses, beam polarization and its mode structure, etc. Workpiece material and machine-related parameters are feed rate, focal spot overlap, etc. In addition to this, existing factors such as power fluctuations, intensity distribution, and thermal effects on optical components normally not controlled by the operator, also influence the machining process. In order to improve the reliability, tolerances and precision of laser machining, a closed-loop process control is required and utilized to compensate for the external and internal process disturbances, which essentially affect the final quality of the machined workpiece.

This paper deals with one of the important tasks in the analysis and the design of a control system by means of mathematical modelling of the laser material-removal process - a subject of automatic control. If we consider the process dynamics, the machining phenomena is a space-time interaction of the laser beam with workpiece material which results in the removal of a small quantity of material with each incident laser pulse. The quality of the machined workpiece depends on the control of fluctuations within the process parameters. The overall system approach ties together four main factors associated with the dynamic processes that play an important role during laser machining and influence the quality of the machined workpiece. These factors are (a) the kinematic and dynamic disturbances within the workpiece motion system, (b) the space-time fluctuations of the laser beam, (c) the laser-material interaction as a dynamic process, and (d) the forming of the workpiece surface as a dynamic process. The novel approach presented herein performs the dynamic analysis of a laser machining system for diagnostics, control and process optimization purposes.

Laser material-removal process - a "black box" approach

The general structure of a closed-loop control system can be represented as shown in Fig. 1, which consists of:

a) the controlled process, whose mathematical model describes a transformation of controlled variables into output variables
b) the controller, represented by a hardware/software system whose mathematical model is a control algorithm in view of transformation of input variables into controlled variables including the feedback variables
c) sensors, whose mathematical model represents a transformation of measured into feedback variables.

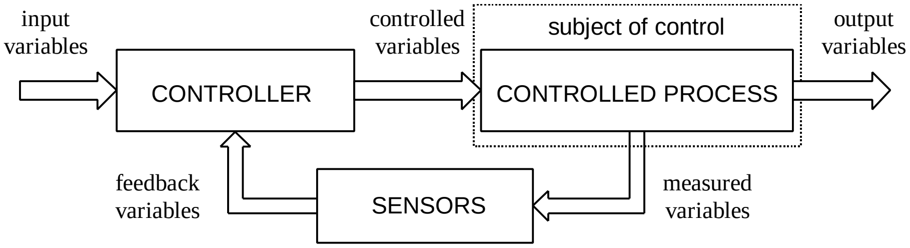

Fig. 1. Generalized structure of the closed-loop control system.

In view of the laser machining process, the controller represents the laser and CNC motion subsystems and provides the controlled variables. The controlled process box represents the laser material-removal process as a subject of automatic control. Based on this statement, the task of dynamic modelling of the controlled process consists of a mathematical description of the "black box" of the laser material-removal process as shown in Fig. 2. Here, the mathematical description represents the transformation of the controlled variables, such as parameters and characteristics associated with the laser beam and feed motions into output variables such as the geometrical features of the machined workpiece and its profile. A mathematical model can represent the transformation of these variables and predict or estimate the machined workpiece surface profile based on the dynamic behavior of the laser beam and the feed motions, and physical/mechanical/thermal properties of the machined material.

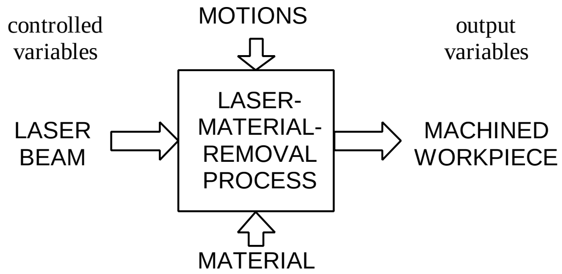

Fig. 2. "Black box" of the laser material-removal process.

Dynamic representation of the laser machining system

The laser machining system is a complex electro-optical-mechanical system consisting of:

- the laser/optics as a subsystem, which delivers the laser beam into the processing zone
- the workpiece motion subsystem which includes a base, electro-drives and translation stages to provide the feed motions.

The ideal laser machining system must provide adequate conformance of the laser beam focal spot into the workpiece surface in accordance with the predetermined tool path. However, laser machining experiments indicate that the geometric feature qualities of the machined workpiece are not only defined by the predetermined tool path but also influenced by the dynamic processes within the processing zone. Mainly, the following four dynamic processes must be considered.

The first process consists of kinematic (e.g., geometrical errors) and dynamic (e.g., frictional process) disturbances associated with the workpiece motion subsystem. A combination of these disturbances produce uneven feed motions and affects the synchronization with the individual laser beam impulses. These variations can be as high as 35% in the feed rate even for motion tables with air bearings.

The second process within the laser/optics subsystem is associated with the space-time fluctuations in the laser beam parameters and its characteristics, such as focal spot diameter, power density, mode structure, intensity distribution, frequency, polarization, etc. These inherent variations are due to imperfections within the laser, its control system, and the thermal gradients in the optical beam delivery system.

Laser-material interactions play an important role in the material removal process. Therefore, the formation of the workpiece profile must be considered as the ultimate result of the combined effect of all the dynamic processes involved in the interaction, including the laser/optics and feed motion subsystems, and the thermodynamic actions/changes in the processing zone. Based on this discussion, the dynamics of the laser-material interaction and the formation of the workpiece profile are respectively the third and the forth dynamic processes that influence the machined surface quality.

The laser-material interactions form a non-linear dynamic link between the laser beam and the machined workpiece. As a first approximation, this non-linear link can be described as a combination of two components. The first component that represents the linear properties of the laser-material interaction process is a dynamic operator. This operator mathematically describes the transformation of the laser beam into corresponding volume of material removal. We call this component the dynamic characteristic of the laser-material interaction process. The second component corresponds to the process noise in view of space-time random process, which symbolizes non-linear singularities of the laser-material interaction process and forms an additional component.

The final source is the dynamics of the workpiece profile formation. In reality the dimensional profile of the laser beam focal spot does not conform to the workpiece profile due to the space-time non-stationary thermodynamic process disturbances in the processing zone. These thermodynamic disturbances modify the physical/chemical properties of the workpiece material that leads to changes in the machined area.

Generalized dynamic modelling

A schematic representation of the laser machining system is shown in Fig. 3 and the laser material-removal process dynamics is illustrated in Fig. 4. The generalized mathematical model can be expressed as follows:

$$\begin{cases} \dfrac{d\mathbf{r}(t)}{dt} &= \Phi\left(\mathbf{r}(t), \mathbf{v}(t), \mathbf{f}(t), \mathbf{v}^*(t), \mathbf{f}^*(t)\right) \\ \mathbf{R}(t) &= \Psi\left(\mathbf{r}(t), \mathbf{v}(t), \mathbf{u}(t), \mathbf{f}(t), \mathbf{v}^*(t), \mathbf{u}^*(t), \mathbf{f}^*(t), \mathbf{q}^*(t)\right) \end{cases} \tag{1}$$

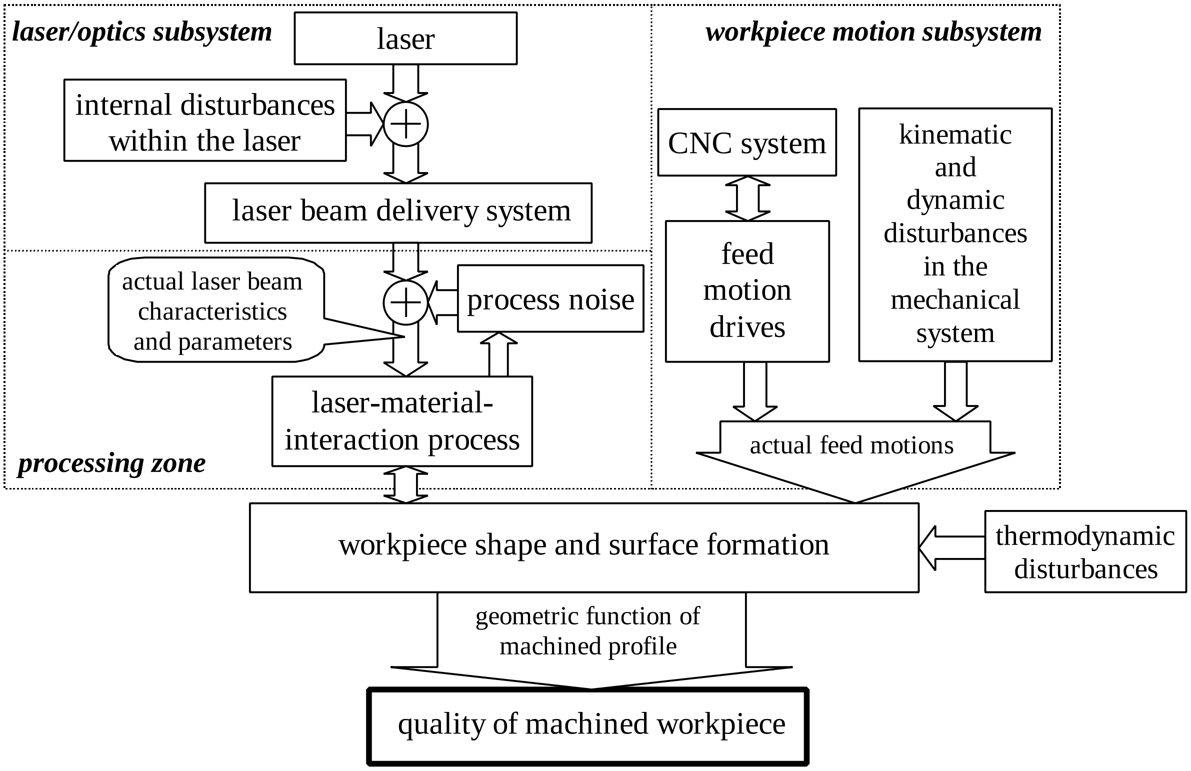

Fig. 3. Schematic representation of the laser machining system.

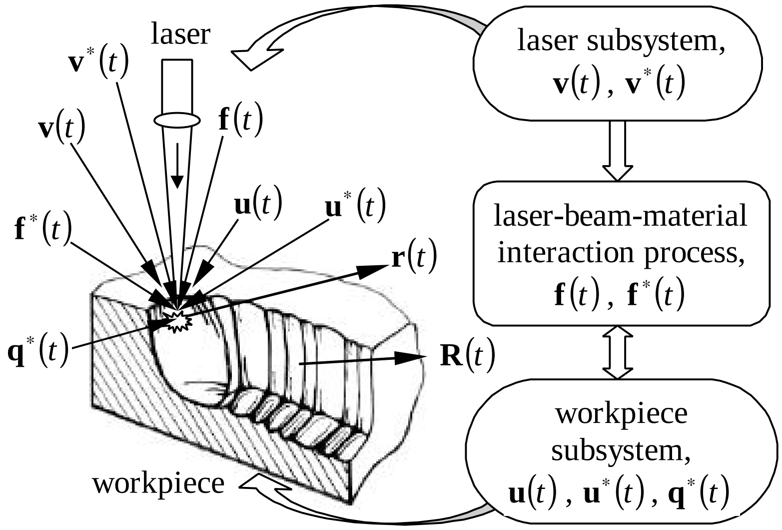

Fig. 4. Schematic representation of the laser material-removal process dynamics.

where $\mathbf{r}(t)$ is the vector for the volume of material removed and is defined in terms of the standard machine-tool coordinate system (X, Y, Z). The components of this vector $\mathbf{r}(t)$ describe material removal in time and space during simultaneous interaction of laser beam impulses and feed motions. $\mathbf{R}(t)$ is the vector for the final quality of the machined workpiece, which includes the dimensional features, surface roughness, hardness, etc. $\mathbf{v}(t)$ is the control vector for the laser/optics subsystem having several variables as its components, viz. focal spot diameter, power density, intensity distribution, mode structure, pulse width, frequency, etc. $\mathbf{v}^*(t)$ is the vector for the internal disturbances in the laser/optics subsystem and represents the random components of $\mathbf{v}(t)$ elements. $\mathbf{u}(t)$ is the control vector for the workpiece motion system having its own variables as its components, viz. machining tool path, feed rate, spot overlap, etc. $\mathbf{u}^*(t)$ is the vector for kinematic and dynamic disturbances within the workpiece motion subsystem and represents random components of $\mathbf{u}(t)$ elements. $\mathbf{f}(t)$ is the vector for parameters and characteristics associated with the beam in the laser-material interaction zone and can not be measured in reality. $\mathbf{f}^*(t)$ is the vector for process noise, which represents an additional component for $\mathbf{v}^*(t)$ affecting the laser beam characteristics inside the processing zone. $\mathbf{q}^*(t)$ is the vector for thermodynamic disturbances in the interaction zone and finally influences the machined surface quality. $\Phi(\cdot)$ and $\Psi(\cdot)$ are functions of the vector variables.

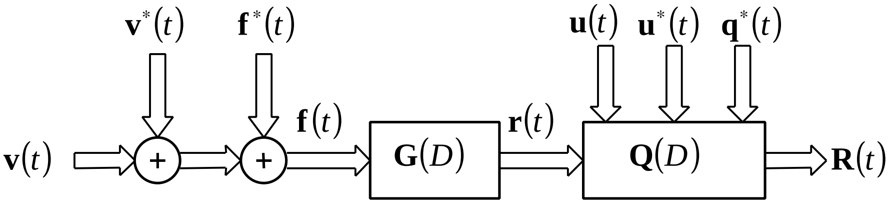

Fig. 5. System representation of the laser-material-removal-process dynamics.

The generalized mathematical model (1) of the laser machining system's dynamic structure is shown in Fig. 5 and is expressed in terms of linear approximation as follows:

$$\begin{cases}\mathbf{f}(t)=\mathbf{v}(t)+\mathbf{v}^*(t)+\mathbf{f}^*(t)\\ \mathbf{r}(t)=\mathbf{G}(D)\mathbf{f}(t)\\ \mathbf{R}(t)=\mathbf{Q}\big(D,\mathbf{u}(t),\mathbf{u}^*(t),\mathbf{q}^*(t)\big)\mathbf{r}(t)\end{cases} \tag{2}$$

where $\mathbf{G}(D)$ is the transfer-function matrix of the laser-material interaction process which transforms the vector of the actual laser beam $\mathbf{f}(t)$ into corresponding volume of the material removal $\mathbf{r}(t)$; $\mathbf{Q}(D)$ is the transfer-function matrix of the workpiece profile formation as a dynamic process, which transforms the actual material removal volume $\mathbf{r}(t)$ into the final quality of the machined workpiece $\mathbf{R}(t)$ taking into account the control vector of the motion system $\mathbf{u}(t)$, kinematic and dynamic disturbances $\mathbf{u}^*(t)$, and thermodynamic disturbances $\mathbf{q}^*(t)$; $D = d/dt$ is the differential operator.

Conclusions

A systematic approach for the dynamic modelling of the laser material-removal process has been presented. The concept is based on the laser-material interaction as a dynamic process. The in-process disturbances within the laser/optics and workpiece-motion subsystems, the fluctuations associated with the process parameters and the thermodynamic disturbances have been included.

Introduced analysis lays a foundation for performing the following tasks:

- dynamic modelling and parametric identification of the transfer function matrix of the laser-material interaction process $\mathbf{G}(D)$
- dynamic modelling and parametric identification of the transfer function matrix of the workpiece profile and surface formation $\mathbf{Q}(D)$
- modelling/estimation of the statistical characteristics of the disturbances within the laser/optics $\mathbf{v}^*(t)$ and the workpiece-motion $\mathbf{u}^*(t)$ subsystems, the process noise $\mathbf{f}^*(t)$ and thermodynamic disturbances $\mathbf{q}^*(t)$

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