Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 45 (2016) 175 – 178

www.elsevier.com/locate/procedia

3rd CIRP Conference on Surface Integrity (CIRP CSI)

# A study on the stair stepping effect in direct metal laser sintering of a nickel-based superalloy

Evren Yasa[a]*, Ozgur Poyraz[a], Ezgi Ugur Solakoglu[a], Guray Akbulut[a], Soner Oren[a]

[a]*Tusas Engine Industries Inc., 26003, Eskisehir, Turkey*

* Corresponding author. Tel.: +90-222-2112100; fax: +90-222-2112101. *E-mail address:* evren.yasa@tei.com.tr

**Abstract**

Like other additive manufacturing processes, the stair stepping effect is the main reason of a low surface quality in direct metal laser sintering (DMLS) due to the layered nature of the process. Furthermore, the processing variables such as build direction, layer thickness and process parameters may significantly alter the obtained surface quality as a result of this effect. This paper aims to predict the stair stepping effect on the surface quality for free form surfaces with validations on a demonstration part representative of a group of aero-engine components.


Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)

*Keywords:* Direct Metal Laser Sintering; stair stepping effect; surface quality.

## 1. Introduction

Direct metal laser sintering (DMLS) is a powder-bed additive manufacturing process which is used to produce functional 3D parts or prototypes from a wide range of powder materials with good mechanical properties compared to those of cast or wrought materials. Its sectorial utilization expands in the production of medical and aerospace parts, taking the advantage of relative low volume, design freedom, customized and lightweight structures. Despite the appealing opportunities offered by DMLS, there are still some challenges to be overcome for a wider acceptance of the process in sectors with high requirements.

The surface quality obtained by DMLS is one of the inherent limitations of the layer-based process. The main reason for low surface quality is actually the layered nature of the DMLS process, and is similar to other additive manufacturing technologies resulting in a stair-stepping effect [1]. On top of that, the processing variables such as build direction, layer thickness and process parameters may significantly alter the obtained surface quality. Example study [2] indicates that, the difference between resulting surface roughness values can be more than doubled depending on build direction for the same process and material. There are two commonly used methods for improving surface quality in additive manufacturing. In the first one, secondary or post processes may be utilized [3, 4] and in the second one, different process parameters, layer thicknesses, build directions or scan strategies like re-melting can be evaluated [5, 6]. However, both options will increase the cost due to material consumption, machine time and labor. Moreover, the surface quality on internal and vertical walls cannot be enhanced by these methods. Current research involves various studies revealing preventive actions to overcome possible surface quality issues before they occur.

The majority of the work in the open literature is dedicated to determining process limits, and to setting design rules within the relevant additive manufacturing process [7-10]. Most of the research demonstrates the causes of surface roughness and points to the importance of stair stepping on surface roughness, particularly for up-facing surfaces [7-9]. Detailed predictive models are needed for additive


Peer-review under responsibility of the scientific committee of the 3rd CIRP Conference on Surface Integrity (CIRP CSI)
doi:10.1016/j.procir.2016.02.068

manufacturing, in order to anticipate the impact of process variables on the surface roughness. Several studies included predictive models mostly for simple geometries with planar surfaces and specific angular increments [11-13]. There is still a need for research on surface quality prediction of free form surfaces produced by additive manufacturing processes, and of course stair stepping effect has a substantial influence on the surface quality. Moreover, stair stepping effect triggers surface irregularities including the waviness. The waviness has known influence on aero engine performance, leading to higher losses in certain modules such as compressors [14].

This paper begins by describing the prediction methodology and details the flow of the proposed method, explaining each individual step and related geometry. The following sections detail the experimental procedure and experimental results, and compare them to the model prediction. Finally, the predictive model is demonstrated for a representative geometry for aero-engine components.

## 2. Prediction of stair stepping effect

The stair stepping effect is a limitation for all layer manufacturing techniques particularly in the production of inclined or curved surfaces. It depends on various factors such as inclination angle as well as the layer thickness [15]. When considering planar surfaces of the part, the stair stepping effect is expected to increase with increasing layer thickness and decreases with increasing inclination angle. Similar to the inclination angle, on free-form surfaces, the curvature radius is another influencing factor. However, it is not easy to make rough estimates of the stair stepping effect for a particular radius value, since it changes also with the angle of the arc and concavity or convexity. Besides, the size distribution of the powder particles with a lowest mean radius possible reduces the stair-stepping effect. Yet, the need for homogenous powder coating limits the minimum particle size.

Since it is not possible to employ a general geometric model for free form geometries, the proposed prediction method utilizes a numerical approach. The methodology starts with a preparation step where the essential inputs such as CAD geometry and design requirements for the surface quality are provided. Design requirements indicate the regions and directions to be inspected for surface quality as a consequence of functional surface characteristics (e.g. air flow surfaces). Since the z-axis generally denotes the build direction in AM, the x-axis is selected to perform the calculations. This is, of course, important for the contact measurement methods. For non-contact methods, the data of entire region can be acquired independent of the chosen axis. Later on, point coordinates are extracted from the contour line utilizing z-axis increments equal to the layer thickness (see Fig. 1).

The total waviness, $W_t$ is a sum of $W_V$, the maximum valley and $W_P$, the maximum peak as shown in Eq. (1).

$$W_t = W_V + W_P \tag{1}$$

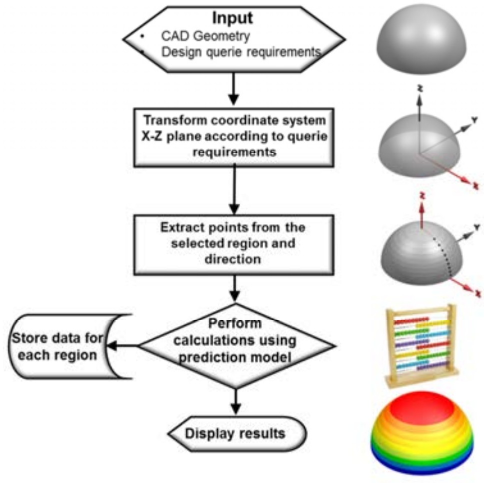


**Fig. 1** The flowchart of methodology with illustrations

The study considers two main input factors, surface profile and layer thickness in the prediction model. The positions of the peak and valley points are varied. Moreover, the shape of the section of stair steps is circular due to melting and wetting phenomena. Fig. 2 shows an illustration of three consecutive layers with layer number indicated by $n$, layer thickness indicated by $t$, coordinate values by $X_n$ and $Z_n$. The section of a surface profile is given along the z-axis. The surface profile is divided into linear segments and the center points of two consecutive layers are connected with horizontal and vertical lines to form a unit triangle between each layer. The angle for each layer is indicated by $\theta$; the peak is indicated by $W_{PJ}$; and the valley is indicated by $W_{VJ}$.

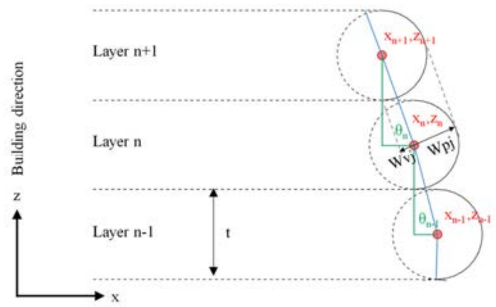


**Fig. 2** Schematic for prediction model

According to prediction model, $W_{PJ}$ and $W_{VJ}$ can be expressed by the following equations. In the equations, $t$ represents layer thickness, and $\theta$ represents the inclination angle of unit triangle between two consecutive layers.

$$W_{PJ} = \frac{t}{2} \tag{2}$$

$$W_{VJ} = \frac{t}{2}.\cos\theta \tag{3}$$