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Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Modeling and optimization of surface roughness in single point incremental forming process

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ARTICLE INFO

Article history:
Received 24 June 2014
Accepted 13 January 2015
Available online 18 February 2015

Keywords:
Incremental forming
Surface roughness
Artificial neural networks
Support vector regression
Genetic programming
Genetic algorithm

ABSTRACT

Single point incremental forming (SPIF) is a novel and potential process for sheet metal prototyping and low volume production applications. This article is focuses on the development of predictive models for surface roughness estimation in SPIF process. Surface roughness in SPIF has been modeled using three different techniques namely, Artificial Neural Networks (ANN), Support Vector Regression (SVR) and Genetic Programming (GP). In the development of these predictive models, tool diameter, step depth, wall angle, feed rate and lubricant type have been considered as model variables. Arithmetic mean surface roughness (R_a) and maximum peak to valley height (R_z) are used as response variables to assess the surface roughness of incrementally formed parts. The data required to generate, compare and evaluate the proposed models have been obtained from SPIF experiments performed on Computer Numerical Control (CNC) milling machine using Box–Behnken design. The developed models are having satisfactory goodness of fit in predicting the surface roughness. Further, the GP model has been used for optimization of R_a and R_z using genetic algorithm. The optimum process parameters for minimum surface roughness in SPIF have been obtained and validated with the experiments and found highly satisfactory results within 10% error.

1. Introduction

Incremental sheet forming is a potential process used for sheet metal prototyping and low volume production applications. This process requires very simple tooling and can be carried out by CNC milling machine. Tool diameter, step depth, feed rate, spindle speed, friction, wall angle and tool path are some of the important process parameters that affect the mechanics of forming process. More processing time and less geometrical accuracy over conventional processes are some of the limitations of this process [1]. A schematic diagram of Incremental Sheet Forming (ISF) has been shown in Fig. 1.

In ISF, the sheet is pressed locally by a hemi-spherical headed tool. The motion of the tool is controlled along a proper trajectory to get the required shape. During the motion of the tool over the sheet, friction between tool and sheet plays a very vital role. In dry conditions, friction between tool and sheet is

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http://dx.doi.org/10.1016/j.jmrt.2015.01.003

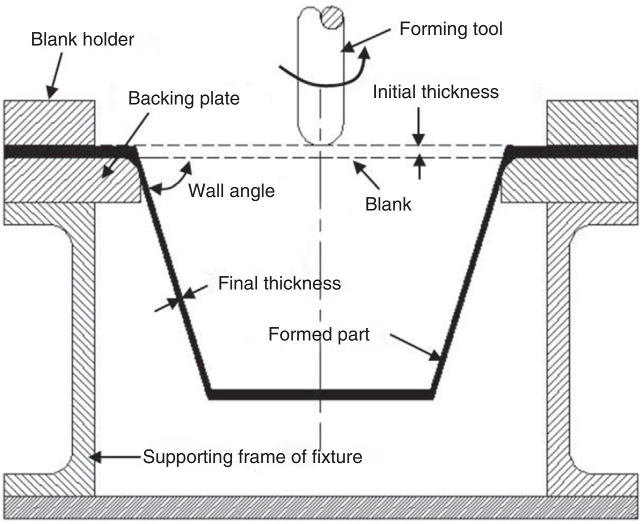

Fig. 1 – Schematic representation of SPIF process.

very high and thus it leads to galling and poor surface finish. It may also lead to premature failure of the part. Some kind of lubrication is very essential to minimize the friction and to get a good quality part. The surface quality of the part is also affected by other parameters such as tool diameter, wall angle, step depth, feed rate and sheet material.

Some researchers made an effort to develop analytical and empirical models to understand the effect of process parameters on surface roughness. Hagan and Jeswiet [2] conducted experiments to study the effect of spindle speed and step depth on mean surface roughness, RMS roughness, maximum profile height and mean peak to valley height. They proposed an empirical model to calculate the peak to valley height of incrementally formed components. Bhattacharya et al. [3] studied the effect of process parameters on formability and surface roughness of Al 5052 material by forming truncated conical and pyramidal frustums respectively. They developed the empirical equations for maximum formable wall angle and surface finish as a function of process parameters. Durante et al. [4] developed the analytical models for average roughness, maximum roughness and mean spacing between the profile peaks as a function of tool radius, wall angle and step depth. They also validated the models by creating pyramidal components with AA7075 T0 material.

The literature study reveals that very few studies have been done on development of analytical and empirical models for evaluation of surface quality in incremental forming. On the other hand, the machine learning techniques became very popular in the recent past in developing the most efficient predictive models in manufacturing [5–9]. These techniques are capable of providing better results than the analytical methods due to their capability of learning nonlinear behavior. But, no literature is available on the application of machine learning techniques to predict the surface roughness of parts formed in incremental forming. Thus, the aim of this study is to develop the mathematical models that relate the surface roughness with different process parameters in incremental forming. For this, three different machine learning techniques, namely, Artificial Neural Networks (ANN), Support Vector Regression (SVR) and Genetic Programming (GP) have been used. This study compares the results obtained from these three modeling methodologies. Further, the process was optimized for minimum surface roughness using Genetic Algorithm (GA). The minimum surface roughness values with corresponding optimum process parameters are reported in the subsequent sections and validated with experiments.

2. Experimental setup and process parameters

Incremental forming experiments were performed on BRIDGEPORT HARDINGE 3-axis CNC milling machine with Fanuc controller. The machine has a maximum spindle speed of 8000 rpm and a drive motor of 15 kW. It has a maximum stroke length of 600 mm × 540 mm × 540 mm in x, y and z directions respectively. The tool path required to form different part geometries was generated with Pro-Manufacturing software and has been transferred to the machine through RS-232 port. Fig. 2 shows the experimental setup of incremental forming process.

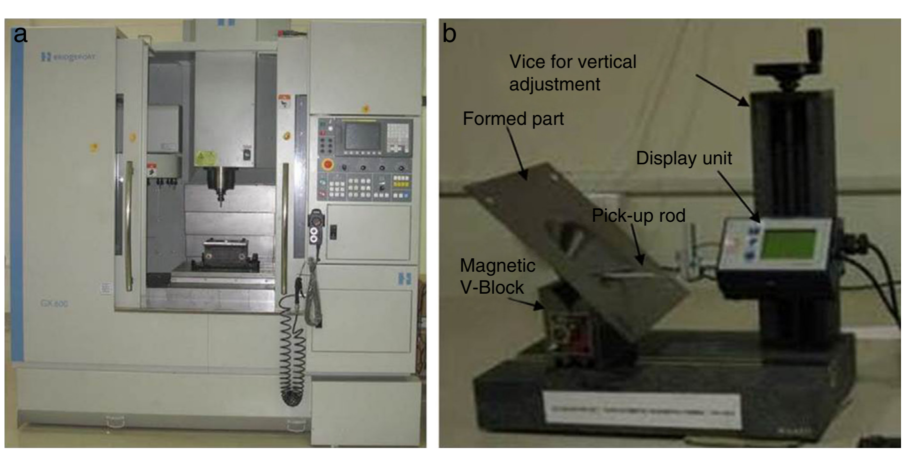

Fig. 2 – Experimental setup for single point incremental forming (a) CNC milling machine with fixture (b) formed part geometry for surface roughness measurement.