Measurement 78 (2016) 296–308

Contents lists available at ScienceDirect

Measurement

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

Application of a hybrid optimization technique in a multiple sheet single point incremental forming process

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ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form 19 October 2015
Accepted 20 October 2015
Available online 24 October 2015

Keywords:
ANOVA
Regression
RSM
SPIF
TGRA

ABSTRACT

Incremental forming of sheet metals is a reliable area where industry can focus in the future due to enormous opportunities available for automation. Due to the slow speed and low accuracy, the process has not yet been embraced by industry. Single point incremental forming with multiple sheets can improve the production rate considerably. In this paper, a hybrid optimization technique is used by combining Taguchi grey relational analysis (TGRA) and response surface methodology (RSM) to determine an optimal combination of input process parameters, such as the number of sheets, the tool diameter, the feed rate, the spindle speed and the vertical step depth, required to obtain favorable responses. Promising results were obtained from the optimization, and the results were validated using a confirmatory experiment demonstrating that the process could be effectively improved and that the optimization technique is robust.

1. Introduction

Incremental forming is a new research area of focus within industry and academia because it is a die-less forming process [1]. In the new era of manufacturing, incremental forming provides various opportunities for designers and manufacturers as dies are considered to be major obstacles to automation [2]. With the advent of friction stir welding, these two processes can be combined together to automate the sheet metal forming processes. Therefore, these two processes together have the capability to revolutionize future industries especially in the case of automobile and aircraft industries. Asymmetric incremental sheet forming (AISF) can be defined as a process that uses a forming tool that is in continuous contact with the sheet metal and as a process that does not make use of dies. There are two types of incremental forming: single point incremental forming (SPIF) and two point incremental forming (TPIF). In both processes, only one forming tool is used, but in TPIF, the sheet metal is pressed at two points simultaneously. Therefore, in TPIF, a partial die is used in addition to the forming tool. The partial die provides an upward thrust, and the forming tool deforms the material; thus, TPIF is not truly a die-less process [3]. A three axis milling machine is a commonly used machine tool for incremental forming, and the forming tool used is either rounded corner or ball made of hardened carbon steel with a diameter of 8 mm, 10 mm or 12 mm. The major

Abbreviations: AISF, asymmetric incremental sheet forming; ANN, artificial neural network; ANOVA, analysis of variance; CAD, computer aided design; CMM, co-ordinate measuring machine; CNC, computerized numerical control; GRA, grey relational analysis; GRG, grey relational grade; MSSPIF, multiple sheet single point incremental forming; PCA, principal component analysis; rpm, revolutions per minute; RSM, response surface methodology; S–N ratio, signal to noise ratio; SPIF, single point incremental forming; SR, surface roughness; TGRA, Taguchi grey relational analysis; TPIF, two point incremental forming; VMM, video measuring machine.

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http://dx.doi.org/10.1016/j.measurement.2015.10.025
0263-2241/

drawbacks of the incremental forming process are spring back of the sheet material, a low accuracy, an orange peel effect, a pillow effect and a low production rate [4].

The incremental sheet forming process is particularly useful in rapid prototyping applications of small and medium sized batches due to the following advantages: lower cost, the use of a conventional CNC machine, quick design changes, direct production of parts from a CAD file, stresses acting in the material are reduced, the possibility of forming parts having any dimension, a good surface finish of the formed parts, molds and dies can be avoided and a high material formability. The low production rate of the incremental forming process can be overcome by employing multiple sheets instead of single sheets. Recently, multilayer sheet forming processes have been used widely in various aerospace, automobile and chemical engineering works due to their inherent benefits, such as a greater formability of a less-formable part, an improvement in corrosion resistance and wear resistance, each layer having variable electrical conductivity, a low spring back, reduction in wrinkles and, ultimately, in weight and a low manufacturing cost [5]. A multiple sheet single point incremental forming (MSSPIF) process can be widely used in the manufacturing of electrical components where multiple sheets are used to reduce the eddy current effect. Rapid prototyping of metal parts is becoming increasingly important because testing can be performed in the same material as the real part, and validation will be more accurate. Rapid prototyping using a MSSPIF process will reduce the time taken and increase the production rate of non-functional components [6], such as automotive body panels, aircraft structures and ship hulls. Sheet metal panels embedded with honeycomb structures and porous structures are gaining importance currently because they reduce the weight of the structures considerably. A MSSPIF process can be effectively used to process these panels. However, a very few number of studies have been conducted to determine the impact of various input process parameters on responses. Very few studies investigating the impact of process variables using RSM have been performed on the MSSPIF process. Therefore, it is appropriate to focus on the optimization of the MSSPIF process. In this work, the MSSPIF process is conducted, and a hybrid optimization technique (TGRA–RSM) is introduced for the first time in the SPIF process to optimize the process variables.

Being a new process, literature on the MSSPIF is scarce. Silva et al. [7] conducted a single point incremental forming of tailored blanks produced by friction stir welding. In this work, the authors used a dummy sheet above the tailor-welded blank to avoid direct contact of the tool with the blank. The use of the dummy sheet was expected to affect the formability because, theoretically, the dummy sheet increases the radius of the tool and increases the meridional stress (σ_{φ}), which, therefore, increases the hydrostatic stress causing a decrease in the formability of the process, but the experimental results showed that the decrease in formability was very small. Junchao et al. [8] conducted an experimental and numerical investigation of incremental sheet metal forming with an elastic support and proposed an improved compensation strategy for the shape error. Fiorotto et al. [9] performed a preliminary study on the single-point incremental forming of composite materials, and Jackson et al. [10] studied the incremental forming of sandwich panels and found that the through thickness strains experienced by both materials were the same.

The various methods used for the multi-response optimization problems include grey relational analysis (GRA), principal component analysis (PCA), regression analysis, data envelopment analysis, response surface methodology (RSM), artificial neural networks (ANN), fuzzy logic and goal programming [6]. The grey relational grade was used as the performance measure in GRA, and the grade values were maximized irrespective of the nature of quality characteristics [11]. RSM is a collection of mathematical and statistical methods that are used for modeling and analysis of technical and other problems in which response parameters are controlled by various input process parameters [12]. This method actually provides a correlation between the input and the response variables studied and provides a good amount of information, even when the number of experiments is comparatively low [13]. The interaction effect of input process parameters on responses can also be studied using this method. RSM easily elucidates the effect of a binary combination of input process parameters on the response values [14]. The empirical model can be used in further analyses, which eliminates the needs to conduct experiments again [15]. This technique is widely used to design experiments, analyze various processes, model buildings, understand the effect of various factors, find optimum parameter combinations and reduce the number of experiments [16]. Fewer studies are found in the area of incremental sheet metal forming process where a Taguchi L_{18} orthogonal array was used to determine the levels of input variables to obtain optimum response parameters using Taguchi grey relational analysis–response surface methodology (TGRA–RSM). In this work TGRA–RSM [17–21,23–25] was used to optimize the response parameters, such as the forming time, the wall angle, the formability, the surface finish, and the spring back.

2. Materials and methods

The detailed experimental methodology is given in Fig. 1.

Researchers in the incremental sheet forming process have, so far, concentrated mainly on materials such as aluminum and its alloys [1]. Because few studies were found that focus on the incremental forming of copper sheets, in this work commercially pure copper sheets with a thickness of 0.4 mm were used. The sheet metal forming process was performed at Oxford industries in Ariyamangalam, which is near Trichy, using a vertical CNC milling machine made by Bharath Fritz Werner Ltd, Bangalore. The fixture and tool used for the forming process are shown in Fig. 2. Sheets were cut into a 150 mm $\times$ 150 mm size, and circular grids with a 1.98 mm diameter and 0.05 mm depth were made using laser engraving. The sheets were arranged one below the other to perform the multi-sheet single point incremental forming. Tools were made of EN-8 steel, and