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Experimental investigation, prediction and optimization of cylindricity and perpendicularity during drilling of WCB material using grey relational analysis

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ABSTRACT

Manufacturing is always the heart of majority of industries. Drilling is an extremely important and an essential machining process which requires a lot of attention as in most of the cases it is required for assembly purposes. Majority of the holes produced during drilling are made with the help of Vertical Machining Centre (VMC) meant for pin- hole assembly. Though the tolerance is within limit, assembly problems arise due to the improper geometry of these holes. Various geometrical tolerances like cylindricity, circularity, perpendicularity and position errors are responsible for such assembly problems. This investigation is focussed on cylindricity and perpendicularity in the drilling of Wrought Cast Steel Grade B (WCB) material using SOMX 050204 DT insert. In this work, effect of machining variables like cutting speed, feed rate and depth of cut (canned cycle) are investigated and optimized using grey relational analysis (GRA). Reliable experiments are conducted based on a 3^3 full factorial, replicated twice. Second order regression models are developed for predicting cylindricity and perpendicularity. The models' adequacy has been checked by calculating correlation coefficient. It shows that the developed models are well fitted for the prediction of responses within the specific range of input variables.

1. Introduction

Achieving better quality to improve performance of the product is the basic necessity of every industry. Certain challenges like dimensional/geometrical tolerances, good surface finish, high production rate, reduced tool wear are encountered by many production industries. Increase in the metal removal rates lead to high productivity in machining operations. It is very difficult to balance the high metal removal rate and tight tolerance targets, because of their nature. The degree of conformance of the finished part to dimensional and geometric specifications has four major contributors: geometric errors of the machine construction, thermally induced errors from heat sources associated with the machine/cutting process, trajectory following errors caused by controller and machine structural dynamics, and errors due to cutting forces [36]. Bryan J. explained the significance of heat generated during machining. Machine axes, spindle motor and shearing action during cutting are responsible for heat generation. This heat distort the machine geometry and causes error in the machined parts [37]. Schmitz et al. have presented a case study on comparison of error sources in high- speed milling. They have considered geometrical, thermal, contouring and cutting force related errors. Their analysis shows that the cutting force error is the most dominant one compared to all other errors for certain choices of spindle speeds [38]. Ramesh et al. reviewed various error compensation techniques related to machine tools. They have considered three major types of error such as geometric, thermal and cutting force induced errors. The paper reports the work done in analysing the various sources of geometric errors that are usually encountered on machine tools and the methods of elimination or compensation employed in these machines. Even cutting force induced errors as well as thermal errors and its compensation techniques are very well discussed [39–41]. Thus it can be said that deflection of tool, workpiece, machine spindle and fixture can be regarded as the sources of dimensional errors in machining [7,8]. As high precision assemblies cannot be analysed with the assumption that form errors are negligible. So, serge et al. have proposed and built a geometrical model based on the modal shapes of the ideal surface [51].

Many components have more than one geometrical feature required for assembly. In such cases it is required to find several geometric tolerances on a single part, which is very crucial from the

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inspection point of view. Moroni et al. proposed a methodology for planning CMM sampling strategies for multiple tolerance based on the minimization of inspection costs [44]. Estimating any geometrical tolerance requires to sample a cloud of points on the feature to check and then to fit an ideal substitute geometry with respect to evaluation of errors. Generally points are sampled by means of a CMM and then a suitable software algorithm will be applied. Moroni et al. reviewed that some algorithms are slow and some of them give approximated solution. So, a new algorithm has been proposed by them [45]. Antonio et al. consider how deviation on fixturing elements effects the location tolerance of a hole's pattern. They have designed locator positioning, which in turn minimizes the positional tolerance [48].

Exploring the literature it was found that a lot of potential is there in the research domain of geometrical tolerances, as it plays vital role during the assembly attributed to better conformity of components. Majority of the researches are done for various types of errors associated in achieving these tolerances. The error compensation strategies are also developed. Various innovative models and techniques were developed to measure various geometrical tolerances. But the work related to cutting parameters, its investigation, its contribution and its selection to optimize the geometrical errors need some amount of focus, which is presented here.

Geometric Dimensioning & Tolerancing (GD&T) is created to insure smooth assembly of mating parts, to improve quality, and to reduce the cost [1]. GD & T is a symbolic language used to specify the size, form, orientation and location of part features. It is based on the standard, Dimensioning and Tolerancing ASME Y14.5M-1994 which is later on updated as ASME Y14.5-2009 [3]. ISO 1101: 2012 (E), which is an international standard of Geometrical product specifications (GPS) – Geometrical tolerancing – Tolerances of form, orientation, location and run-out, contains basic information and gives requirements for the geometrical tolerancing of workpieces [4,47]. Drawings with properly applied geometric tolerancing provide the best opportunity for unambiguous interpretation and cost-effective assembly. Thus GD & T is a design tool, which helps in reducing the rework due to assembly problems, eventually leading to most economized manufacturing [2]. There are five types of tolerances, namely, Form, Profile, Orientation, Run out and Location. While the four form characteristics are Flatness, Straightness, Circularity and Cylindricity [3,4].

2. Literature review

Kumar et al. [9] investigate the effects of drilling parameters such as cutting speed (5, 6.5, 8 m/min), feed (0.15, 0.20, 0.25 mm/rev) and drill tool diameter (10, 12, 15 mm) on surface roughness, tool wear by weight, material removal rate and hole diameter error in drilling of OHNS material using HSS spiral drill. Their results show that the feed (62.24%) has greater influence on surface roughness and drill tool diameter, cutting speed accounts 13.94%, 11.48% percent contribution respectively on the holes surface roughness. Also feed (83.38%) has greater influence on hole diameter error and cutting speed and drill toll diameter accounts 1.17%, 0.50% percent contribution respectively on the hole diameter error. Shahrajabian et al. [10] investigated the effects of machining parameter and tool geometry (spindle speed, feed rate and tool point angle) during the drilling process of carbon fibre reinforced polymer composites (CFRP) on surface roughness, delamination and thrust force. The experiments on CFRP were conducted to obtain surface roughness, delamination factor and thrust force values based on the full factorial design of experiments, and then analysis of variance (ANOVA) is performed.

Madhavan et al. [11] investigate effect of thrust force during drilling of 10 mm diameter holes in 20 mm thick carbon fibre reinforced plastic composite laminate using HSS, Solid Carbide (K20) and Poly Crystalline Diamond insert drills. Experiments are conducted on a Vertical Machining Centre using Taguchi design of experiments. A model is developed to correlate the drilling parameters with thrust force using Response surface methodology (RSM). Kilickap et al. [12] investigated the cutting parameters (cutting speed, feed rate, tool geometry) affecting delamination of drilling operation. Taguchi L16 method is performed in drilling machine on GFRP composite. Tyagi et al. [13] applied Taguchi methodology for the drilling of mild steel with the help of CNC drilling machining operation with tool use high speed steel. A L9 orthogonal array and analysis of variance (ANOVA) were applied to study the performance characteristics of machining parameter (spindle speed, feed, and depth) with consideration of good surface finish as well as high material removal rate (MRR).

Bharti et al. [14] analysed effect of machining parameters spindle speed, feed rate and tool point on the hole diameter produced and the material removal rate in the Micro-drilling. Taguchi based method along with ANOVA (analysis of variance) and DOE (design of experiments) is implemented for optimized result. In percentage contribution feed rate has about 73.61%, spindle speed has 23.31% and tool point angle has 1.5% influence on the optimum diameter and material removal rate combine. Palanikumar et al. [15] evaluated the effect of spindle speed and feed on delamination in drilling of GFRP composites. They have used twist drill and 4-flute cutter to perform the experiments. The influence of speed is 3.04% and feed is 93.15% on the delamination when drilling with twist drill, while 0.15% and 97.67% when drilling with 4-flute cutter. Results show that the 4-flute cutter has better results compared to twist drill. Reddy et al. [16] analysed effect of machining parameters on surface roughness and roundness error during drilling of AL 6061 alloy. They have used grey relational analysis for optimizing the responses. Kuram et al. [17] developed model to predict thrust force and surface roughness using fuzzy logic and regression. Thrust force and surface roughness during the drilling of AISI 304 with the HSS-E tool measured. Spindle speed, Feed and depth of cut are considered as machining parameters. Sheth et al. [18–20] investigated effect of pressure, RPM and no of grooves on MRR and Spread during the flashing operation of precision steel ball manufacturing. They have developed a fuzzy logic and regression based model to predict MRR and Spread during flashing operation.

Literature survey shows that researchers are working with the surface roughness of the drilled holes. Even though the surface roughness and dimensions are within limit, majority of the assembly problems are occurring due to form error. Various geometrical tolerances like cylindricity, circularity, perpendicularity and position are responsible for such problems in case of holes [21–23]. These geometric tolerances must be applied at the design stage itself to meet the functional requirement along with the assembly producibilityi. However, the production design should be made in terms of machine tool capability so that DFMA can be achieved. In the present study an attempt is made to develop a predictive model of geometric tolerances for WCB material in the context of various drilling input variables. This experimental study may give a new insight to the practising engineers for utilizing the machine tool at optimized level to achieve the best geometry and precision. The same methodology may be adopted for modelling of other geometrical errors also. It may be extended to various machine tools as well for various materials too.

3. Experimentation

3.1. Work piece

The test specimen material is WCB, which is carbon steel with hardness 255 HB and 240 mm × 160 mm × 55 mm size. It has excellent strength properties at high temperature. It is generally