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Taguchi method based optimisation of drilling parameters in drilling of AISI 316 steel with PVD monolayer and multilayer coated HSS drills

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ABSTRACT

This paper focuses on the optimisation of drilling parameters using the Taguchi technique to obtain minimum surface roughness (Ra) and thrust force (Ff). A number of drilling experiments were conducted using the L16 orthogonal array on a CNC vertical machining centre. The experiments were performed on AISI 316 stainless steel blocks using uncoated and coated M35 HSS twist drills under dry cutting conditions. Analysis of variance (ANOVA) was employed to determine the most significant control factors affecting the surface roughness and thrust force. The cutting tool, cutting speed and feed rate were selected as control factors. After the sixteen experimental trials, it was found that the cutting tool was the most significant factor on the surface roughness and that the feed rate was the most significant factor on the thrust force. The results of the confirmation experiments showed that the Taguchi method was notably successful in the optimisation of drilling parameters for better surface roughness and thrust force.

1. Introduction

Austenitic stainless steels are widely used in the chemical, petrochemical, food, and pharmaceutical industries, as well as nuclear energy plants and in stainless appliances [1,2]. However, the machining of these steels is very difficult due to their higher ductility, strength, work hardening rate and lower thermal conductivity [2,3]. As a result of technological developments, coated and uncoated HSS tools, produced via powder metallurgy, are being extensively used in modern drilling processes [4]. In recent years, mono, and multilayer coatings have started to be used at higher cutting speeds and feed rates, as a consequence of significant improvements in coating technology. Thus, a lot of research has been conducted into the cutting tools used with mono, and multilayer coated tools [5]. As titanium aluminium nitride (TiAlN) coatings have higher oxidation resistance [6–8], toughness [9], hardness and corrosion resistance, they have been developed as alternatives to titanium nitride (TiN) coatings. In addition, TiAlN coatings are used especially at high speeds under dry cutting conditions, due to their low thermal conductivity [7] and frictional properties [10–12]. In multilayer coatings, the layers of two or more different coating materials are deposited in a particular sequence. The numerous interfaces created between individual layers of a multilayer coating cause a dramatic increase in hardness and strength [6]. Micro-hardness of TiN and TiC, monolayer and multilayer coated HSS tools were examined and the highest hardness value was found in the multilayer coated tools [12].

Surface roughness is a critical quality indicator for a machined surface and has a bearing on many properties such as: wear resistance, fatigue strength, coefficient of friction, lubrication, wear rate and the corrosion resistance of the machined parts [13]. In addition, depending on the specific cutting resistance of the material, the thrust force required for drilling, is the most important parameter which determines the consumed power and energy costs. A large number of parameters influence the cutting force

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and surface roughness such as: cutting speed, feed rate, depth of cut, rake angle, nose radius, and chip breaker geometry, and therefore, it is very difficult to develop a proper analytical model of the cutting force [14,15]. Many methods such as: artificial neural networks, multiple regression and finite element analysis have been developed for the modelling and prediction of cutting forces and surface roughness. The Taguchi-based optimisation technique has produced a unique and powerful optimisation discipline that differs from traditional practices [16]. Kurt et al. [17] employed Taguchi methods in the optimisation of cutting parameters for surface finish, and hole-diameter accuracy in a dry drilling process. The orthogonal array (OA), the S/N ratio, the analysis of variance, and regression analyses were used to determine the optimal levels and the effects of the drilling parameters on surface roughness and hole diameter. Tsao and Hocheng [18] undertook the prediction and evaluation of the thrust force and surface roughness in drilling of a composite material. Their approach used the Taguchi technique and the artificial neural networks method. Their experimental results show that the feed rate and the drill diameter are the most significant factors affecting the thrust force, whilst the feed rate and spindle speed contribute most to the surface roughness. Asiltürk and Akkuş [19] have studied the optimisation of turning parameters based on the Taguchi method to minimise surface roughness. Their study was conducted using the L9 OA in a CNC turning machine. Tests were carried out on hardened AISI 4140 with coated carbide cutting tools. Neşeli et al. [20] investigated the influence of tool geometry on the surface finish in the turning of AISI 1040 steel using response surface methodology (RSM). Their results indicate that the tool nose radius is the dominant factor on the surface roughness.

This research substantially reduced the number of complex, expensive and time-consuming experiments conducted on CNC vertical machining centres, by determining the optimal drilling parameters needed to obtain better surface roughness and thrust force in drilling of austenitic stainless steel, which has hard machinability characteristics due to higher ductility, strength, work hardening rate and lower thermal conductivity properties with uncoated and coated drills. It is possible to apply this optimisation technique to different applications in manufacturing industry to obtain optimal process parameters such as: cutting parameters, cutting tool geometries and materials, coating types and materials, and cutting conditions, to reduce manufacturing costs and processing time, and to provide higher productivity and quality. In addition, the many scientific studies on the Taguchi method clearly reveal its reliability. Therefore, this study will be useful for future applications in both manufacturing industry and the academic environment.

2. Experimental methods

2.1. Drilling experiments

In this study, AISI 316 austenitic stainless steel blocks were used as the workpiece material. The dimensions of the workpiece were 100 × 170 × 15 mm. Chemical composition of AISI 316 austenitic stainless steel is given Table 1.

Table 1
Chemical composition of AISI 316.

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.05	0.380	0.971	0.039	0.006	16.58	9.94	2.156	0.321

Before the experiments began, the stainless steel blocks were ground to eliminate adverse effects of any surface defect. To minimise the twisting effect, the distance to drill tip from the tool holder was set at 30 mm. This distance was kept constant in all experiments to verify the obtained values. Blind holes were then drilled in the stainless steel blocks. Three holes were drilled to compare thrust force and surface roughness measurements under each machining condition. The mean of these measurements was used for comparison. To protect the initial conditions of each test, a new drill was used for each experiment. The drilling tests were performed by using a Johnford VMC 850 model, three axes CNC vertical machine centre, equipped with a maximum spindle speed of 6000 rpm and a 7.5 kW drive motor. They were performed at four different cutting speeds (12, 14, 16 and 18 m/min) and feed rates (0.1 and 0.12 mm/rev) whilst hole depth was kept constant at 13 mm. All drilling experiments were conducted under dry cutting conditions. The flowchart for optimisation of the drilling parameters is shown in Fig. 1.

2.2. Thrust force measurement

In the drilling experiments, a Kistler piezoelectric dynamometer, model 9257B, was used for measurement of the thrust forces. The signals of thrust force from the dynamometer were transmitted to a Kistler 5070-A type multi-channel (8-channel) amplifier, and then recorded on a personal computer. The dynamometer and work piece were firmly fixed on the table of the CNC machine tool. The experimental set-up for thrust force measurement is shown in Fig. 2.

Components of the cutting forces occurred during drilling process, namely main cutting force (Fc), thrust force (Ff) and radial force (Fr) are shown in Fig. 3. The forces Fr acting on both cutting edges is considered to counterbalance each other. Hence, the forces Fc and Ff only are effective in drill process. As main cutting force values obtained in the drilling tests are significantly smaller than the thrust force values, in this study, three cutting force values were measured, but only thrust force values were evaluated.

2.3. Surface roughness measurement

The surface roughness of the machined holes for each machining condition was measured by using a Mitutoyo Surftest SJ-301 portable surface roughness tester and the average roughness values of surface roughness were evaluated. To measure the surface roughness, the blocks were sliced by wire EDM parallel to the holes axes. The surface roughness was measured parallel to each hole axis from three different points and the average values of the