Online process monitoring of depth of cut of Abrasive Water-Jet cutting of Ti-6Al-4V: A Review

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Abstract: Water jet machining is one of the adaptive unconventional type of machining with significant advantages over the conventional type machining. While working with Ti-6Al-4V under waterjet. It is critical to measure the depth of cut of a material while working on the water-jet machine. Although having more benefits of unconventional water jet machine this may be one of the drawback which may increase machining time. This paper gives review of different research papers on machining of Ti alloys under waterjet, online process monitoring techniques and the various Artificial intelligence techniques used for optimization or prediction purpose.

Key words: Abrasive jet machining, ANFIS, ANN, Machining of Ti alloy, Parameters optimization.

INTRODUCTION

Abrasive water jet (AWJ) is an unconventional method used in machining of difficult-to-machine materials like titanium, tool steels, super-alloys, hardened steels, glass, composites, metal matrix composites, laminates and advanced ceramics by high pressure, high velocity water jet. This list of materials expands daily as people apply the unique properties of fluid jets to industrial problems.

This machining process is now a day's replacing the conventional machining processes due to their significant advantages in present industrial scenario. AWJ machining is a process in which a very high velocity stream of water is used to accelerate particles of an abrasive material, which in turn cuts the workpiece material by erosion principle. It is critical to measure the depth of cut of a material while working on the water-jet machine. Although having more benefits of unconventional water jet machine this may be one of the drawback which may increase machining time. In this project, we are going to predict the depth of cut of Titanium alloy while working under water jet machine using signal processing and then Artificial Intelligence and its hybrid techniques.

The various modern machining processes getting widely used in the industries are: electric discharge machining (EDM), abrasive jet machining (AJM), ultrasonic machining (USM), electrochemical machining (ECM) and laser beam machining (LBM) including various modified versions of these processes. These processes work on a particular principle by making use of certain properties of materials which makes them most suitable for some applications and at the same time put some limitations on their use. These processes involve large number of respective process variables also called as process parameters) and selection of exact parameters setting is very crucial for these highly advanced machining processes which may affect the performance of any process considerably. Due to involvement of large number of process parameters, random selection of these process parameters within the range will not serve the purpose. The situation becomes more severe in case if more number of objectives are involved in the process. Such situations can be tackled conveniently by making use of optimization techniques for the parameters optimization of these processes.

From last few decades, many researchers are working on the process monitoring and optimizing the process parameters in AWJ machining with different materials. Many different Artificial Intelligence (AI) techniques like Artificial Neural Networks (ANN), Fuzzy logic and Adaptive Neuro-fuzzy Inference System (ANFIS) are being used in predicting and optimizing the process parameters. AWJM processes these AI techniques giving the details of formulation of optimization models, solution methodology used and optimization results. Use of these techniques are enhancing the AI revolution and automation. However, these approaches require a large amount of data for training them so as to achieve a reasonable accuracy in the prediction of process parameters. By using time domain, frequency domain and wavelet domain, process parameters can be predicted in online process monitoring. For online process monitoring acoustic emission, cutting force dynamics, sound detection, infrared thermography and vibration sensing techniques can be used. These techniques are used for investigating different phenomena associated with manufacturing process such as tool wear, tool breakage, non-destructive evaluation and surface roughness.

Titanium alloys are among the hardest materials which can sustain maximum temperature at cutting zone. Ti-6Al4V (UNS designation R56400) is an alpha beta titanium alloy featuring high strength, low weight ratio and excellent corrosion resistance. It is one of the most commonly used titanium alloys and is applied in a wide range of applications where low density and excellent corrosion resistance is necessary such as e.g. aerospace industry and biomechanical applications (implants and prostheses). As it is hard to machine this material with conventional we can machine it with AWJ machining.

LITERATURE SURVEY ON ABRASIVE WATER JET CUTTING OF TITANIUM ALLOY:

Li and Wang [1] presented an experimental study of abrasive waterjet machining of Ti-6Al-4V. They have conducted two types of AWJ machining operation drilling & slotting. In hole drilling the relation between drilling and water pressure were investigated, it was found that

the diameter and hole depth were increased as the time of drilling were increased but in a decreasing rate. And in the slot cutting the relation between the water pressure and traverse speed were examined, where they found out that slower traversed speed resulted in deeper depth cut. Hascalik et al. [2] experimented on the effect of variation in traverse speed of AWJ on Ti-6AL-4V. In this study, they have investigated the profiles of machined surfaces, microstructural features of the machined surfaces and the kerf geometries using the traverse speed profilometry and scanning electron morphology (SEM). The results shown that the traverse speed of the jet is a significant parameter on surface morphology and width changes according to it. Boud et al. [3] shown the influence of the abrasive morphology and mechanical properties on workpiece grit embedment. In this experiment, the degree of embedment of five-types of garnet abrasive was measured following the through-cutting of Ti-6Al-4V plate, both on the TSI region and the cut surface. TSI region had much higher degree of embedment (between 12% and 17% depending on abrasive type and cutting conditions) than on the cut face (between 4% and 9% depending on the abrasive type and cutting conditions), due to higher impacts forces in the former area. They 4 concluded that when impacts forces are likely to result in particle fracture, grit shape is not critical parameters in the choice of abrasives for waterjet cutting, both in terms of the cutting efficiency and in the terms of the tendency to embed the grit.

Hlavac [4] investigated the jet trajectory curvature inside the kerf of the water jet. Two types of experiments were done one was to determine a theoretical limit value of material thickness for the traverse speed used for performance of the experimental cut in the given material. The other type of experiment was based on the theoretical calculation of the traverse speed limit for a given material thickness. They derived a function describing the curvature of the jet trajectory inside the cut material and their dependence upon traverse spend, material properties and the jet parameters were established. Fowler et al. [5] investigated the role of jet-workpiece traverse speed, two different grit sizes were used for AWJ cutting. Process parameters under investigation were traverse speed and size of the garnet abrasive particles. All other process variables such as water pressure, nozzle standoff distance, abrasive flow rate, jet impingement angle were kept constant. The stand-off distance was kept 3mm for the maximum Material Removal Rate (MRR). The effect of traverse speed on MRR for both grit size were high at lowest traverse speed and decreased rapidly with increase in the traverse speed. Also increased traverse speed results in reduction in surface waviness for both grit size. High MRR and high surface waviness was observed at low jet traverse also surface waviness increased with no of passes of jet and vice-versa for high traverse speed. For the two grit sizes examined, the MRR, surface waviness, surface roughness was lower for smaller grits.

Machine surface was observed by Seo et al. [6] which recognized the process parametric effects on surface quality, mechanism of MRR and characteristics of generated surfaces by using surface profilometry, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) analysis. It was noticed that entrance kerf width is most significantly affected by the stand-off-distance, exit kerf width and taper ratio by mesh number and the slope by stand-off-distance. J. Wang [7] presented an experimental study on predictive depth of jet penetration models for AWJM cutting of alumina ceramics with controlled nozzle oscillation. He investigated the effects of nozzle oscillations on the depth of cut at small angles by varying combinations of process parameters. In this study the dimensional analysis were used to develop mathematical equation for the depth of cut in terms of process variables, dimensional analysis is a powerful analytical powerful 5 technique in describing the relationship between physical engineering quantities and independent variables. The depth of cut was increased by 82% when the nozzle oscillation angle kept small while other parameters were selected correctly. Also, the combination of high oscillation frequency (10-14Hz) and small oscillation angels (4-60) are considered for maximizing depth of cut in nozzle oscillation cutting. Predictive models for cutting performance measure in AWJ cutting with and without nozzle oscillation have been developed to mathematically predict the depth of cut for optimization and process planning. Van et.al. [8] presented the experimental model in which he studied pocket depth in blind machining using an abrasive water jet in a context where a machine, a pressure and abrasive are given. The results presented shown an extremely good correlation between the depths obtained and obtained using model and depths measured.

Shipway et al. [9] shown that the surface characteristics developed during AWJ-CDM of Ti-6Al-4V to depend upon the process parameters. This experiment examines the AWT milling behavior of Ti6al4v in the terms of the surface properties of the milled components, such as roughness, level of grit embedment and the waviness. The properties of the surface following milling depends on the milling parameters, such as jet-workpiece traverse speed, impingement angle, waterjet pressure and abrasive size. Fowler et al. [10] investigated the effect of particle hardness and shape when AWJ milling Ti-6Al-4v.MRR and surface characteristics were analyzed after single passes of jet. Orifice and nozzle wear due to machining operation can change in characteristics to AWJ. To minimize these effects, both nozzle and orifice were changed. Here parameters investigated were traverse speed, shape and hardness of abrasive particles while other process parameters were kept constant. Results showed that MRR increased at slow traversed speed and decreased rapidly with increased in traversed rate.

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LITERATURE SURVEY ON ONLINE PROCESS MONITORING USING VARIOUS TECHNIQUES:

Hassan et al. [11] predicted that root mean square of acoustic emission (AErms) is more predominant than cutting force response to measure depth of cut in AWJ cutting through online monitoring. They performed an experiment using signal processing method, commonly called as wavelet transform (WT). Vertical cutting force technique is not used due to erosive nature of AWJ. Hloch and Ruggiero [12] used vibration emission technique for the analysis of hydroabrasive cutting. Graphs obtained from experiments shown that higher abrasive mass flow rate shows amplitude growth with low frequencies in case of frequency analysis. AE signals may be continuous type or burst type. Ductile material shows continuous type AE signals whereas unsteady process shows burst type. Mohan et al. [13] used closed loop online monitoring for depth of AWJ penetration using time domain AE signal and Fast Fourier Transform(FFT) analyzer. They also found out power spectrum density (PSD) and cutting efficiency to indicate depth of cut and to control kerf depth in AWJ machining.

Kovacevic et al. [14] monitored thermal energy distribution in AWJ cutting using Infrared (IR) thermography by using opaque materials like Aluminum and Titanium. Aim here is to measure maximum temperature at cutting region and monitoring of radial and axial wear of nozzle. Temperature distribution in AWJ cutting nozzle is also observed using thermocouples and compared those results with IR thermography. Smooth and striated regions were observed in AWJ along kerf. At deformation wear zone i.e. in striated region, workpiece normal force is the better technique for online process monitoring of surface finish. Using parameters like Green's function, auto co-variance function and power spectrum density; Kovacevic et al. [15] established that roughness of surface profile can be decreased by increasing water pressure and component of workpiece normal force. For surface profile monitoring, dynamic workpiece normal force is the main parameter. Axinte and Kong [16] studied multi-sensing technique to determined unnatural events occurring at both nozzle and workpiece levels for 5-axis AWJ machine using variations of input energy at nozzle, utilized energy at workpiece and idle energy at jet. Nozzle clogging and jet penetration can also be determined by using AE technique.

Lisseka et al. [17] used Carbon Fibre Reinforced Polymers (CFRP) plates to predict cumulative burst effect; single burst cannot be identified. They used AE technique for the evaluation of machining parameters. Higher feed rates decrease cutting quality and also decreases cumulative count of bursts exponentially. Changes of machining parameters of CFRP determined by cumulative count of bursts and energy per cutting volume. Experiments performed by Kovacevic [18] shown that impacting jet could be used as an indicator for achieving a depth of cut of AWJ penetration when the workpiece force is generated normally. Also stated that nozzle wear rate is affected by change in waterjet pressure. Mohan et al. [19] determined the nozzle internal diameter which is the most critical part of an AWJ cutting system using Artificial Neural Network (ANN). With the help of piezoelectric actuator mechanism, position of AWJ cutting head can be controlled on a large scale. Corresponding nozzle internal diameter determined by ANN through frequency domain acoustic signals.

Jurisevic et al. [20], interpreted direct proportional relation between RMS value and Standoff distance. On basis of graphs, a correlation between sound signal and standoff-distance can be achieved in time and frequency domain. Jurisevic et al. evaluated the root mean square (RMS) value in the time domain and the amplitude cumulative sum (ACS) of the signal power spectra in the frequency domain. Using generated sound monitoring, stand-off-distance during AWJ cutting process can be controlled.

LITERATURE SURVEY ON APPLICATION OF ARTIFICIAL INTELLIGENCE IN PROCESS MONITORING:

Now a day's Artificial intelligence tools are replacing most of the human tasks in operating and controlling the many processes in industries, which makes processes more accurate and time saving. This literature survey is based on the different AI (Artificial Intelligence) techniques like Artificial Neural Networking (ANN), Fuzzy logic, Adaptive Neuro-fuzzy Inference system (ANFIS) used in predicting and optimizing machine performance parameters in different machining processes. ANN is a computational system inspired by structure, processing method and learning ability of biological brain. ANN consists of input layers, hidden layers and output layers. ANN can be trained by two techniques: supervised and unsupervised/adaptive trainings.

Khan et al. [21] used artificial neural network(ANN) [Multilayer perceptron(MLP) with 3 hidden layer feedforward networks] to develop Artificial Intelligence (AI) model to predict surface roughness of Ti-15-3 alloy in Electrical discharge machining (EDM) with peak current, pulse on time, pulse off time, servo voltage as input parameters. GAO et al. [22] developed a parameter optimization model using Genetic Algorithm(GA) and Artificial Neural Network (ANN) with Levenberg Maquardt algorithm adaptation which represents relation between material removal rate (MRR) and input parameters in Electric Discharge Machining (EDM). Proper machining parameters to get higher MRR are selected by using GA. Among 3 layers of network hidden layer is activated with hyperbolic tangent sigmoid transfer function and output layer is activated by linear transfer function. Joshi and Pande [23] Proposed an intelligent process model for EDM using FEM, ANN and GA. Integrated approach of model development (FEMANN-GA) is based on FEM analysis instead of experimental data (which reduces error and minimizes a cost). Material properties, discharge duration, discharge current and voltage, and duty cycle are used to develop a FEM numerical model then prediction of MRR, TWR, crater depth and radius of workpiece is done by ANN (radial basis function neural network and feed forward back propagation neural network). Genetic algorithm(GA) is used for optimisation of parameters like current, discharge duration, discharge voltage and duty cycle. Pradhan and Bhattacharyya [24] developed a mathematical model to optimise the machining characteristics like MRR, TWR and overcut(OC) using Response Surface Methodology and ANN with peak current, pulse on time, dielectric flushing pressure as input parameters in micro EDM of a Ti-6Al4V super alloy. Process model developed using ANN as one hidden layer with 12 neurons and Levenberg-Marquardt used as a training algorithm. Somashekhar et al. [25] optimised a MRR in micro EDM using ANN with input, hidden and output layers and GA is used to determine optimum process parameters. Gap voltage, capacitance, feed rate and speed are used as input parameters. ANN built in MATLAB is feed forward Neural Network with back propagation algorithm.

Rajmohan et al. [26] optimised machining parameters in drilling of hybrid aluminum metal matrix composites using the grey-fuzzy algorithm. Fuzzy rule-based reasoning integrated with Taguchi's method used to reduce the degree of uncertainty during the decision making. For producing high quality products at low cost L27 3-level orthogonal array is used for experiments. ANOVA is used to find the highly influential drilling parameters that contributes to a high quality product. Kohli et al. [27] optimised material removal rate (MRR) in EDM with copper electrode working on medium carbon steel (AISI- 1040) workpiece using Fuzzy Logic. Discharge current, pulse on time, pulse off time are taken as input parameters. Six angular membership functions are selected for fuzzy models in fuzzy inference system (FIS). Pandey and Dubey [28] improved the geometrical accuracy of the Duralumin sheet in laser cutting and simultaneously minimised kerf width and kerf deviation on both top and bottom sides. Robust parameter design methodology and fuzzy logic theory used to compute fuzzy multi-response performance index. Multi-objective optimization is done by using multiresponse performance index. Also concluded that oxygen gas pressure is the most significant factor followed by pulse frequency (that is directly proportional to pulse energy) in laser cutting of highly reflective and thermally conductive material like Duralumin.

Maher et al. [29] predicted surface roughness of brass using ANFIS in CNC end milling. Spindle speed, feed rate, and depth of cut were used as predictor variables. Fuzzy inference system (FIS) incorporated in the neural network (NN) environment is used to design machine learning algorithm. This hybrid arrangement offers a twin benefit of human-like reasoning quality in conjunction with an adaptive network which is accountable for enlightening the fuzzy rules. Sen et al. [30] ANFIS modeling was utilized to predict the relationship between surface roughness, cutting force and cutting temperature with speed, feed, depth of cut and width of cut as inputs in CNC milling of Inconel 690 using ANFIS. Machine learning algorithm is developed using fuzzy inference system (FIS) incorporated in the neural network (NN) environment. This hybrid arrangement offers a twin benefit of human-like reasoning quality in conjunction with an adaptive network which is accountable for enlightening the fuzzy rules.

CONCLUSION

The optimization of process parameters can be done by using various techniques like fuzzy logy, TLBO, Taguchi method and online process monitoring by using different AI techniques which can make AWJM the best machining process.

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