TEST Engineering & Management

July – August 2020
ISSN: 0193-4120 Page No. 121- 126

Vibration Analysis of Forming Tool and Thin Sheet Metal in Robot-Based Single Point Incremental Sheet Forming

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Article Info
Volume 83
Page Number: 121- 126
Publication Issue:
July - August 2020

Article History
Article Received: *06 June 2020*
Revised: *29 June 2020*
Accepted: *14 July 2020*
Publication: *25 July 2020*

Abstract

Robot-based incremental sheet forming is an approach in producing sheet metal products with innovative and flexibility of the robot technologies. Since the tool condition monitoring plays a vital role in process performance, a robust detection system with reliable pattern recognition on tool wear and product quality need to be developed. This study demonstrates the evaluation of vibration signal using accelerator sensor to correlate with tool wear of forming tool and surface roughness of workpiece in robot-based incremental sheet forming. The experiments were conducted by evaluating the vibration signal generated by the forming tool made of AISI D2 on workpiece of SUS 316. Pattern recognition was gathered to identify and categorize the characterization of tool wear by two cluster; tool in good condition and worn out. The results indicate that the frictional between surface of forming tool and workpiece is directly proportional to tool wear. The increasing of surface roughness on the workpiece can also be seen noticeably with the increasing of vibration on the forming process due to tool wear. This proving that vibration signal can provide the tool wear identification for this ISF process. The development of efficient pattern recognition is important to identify the tool condition and forming tool performance in products quality consistently.

Index Terms: Incremental Sheet Forming, Robot, Vibration, Tool Wear, Surface Roughness.

I. INTRODUCTION

Robot-based incremental sheet forming (ISF) is a new approach in fabricating sheet metal into final products based on appropriate parameters involving robot speed, step size, wall angle, shape and size of the forming tool compared to CNC machine which is involves with feed rate, tool path and lubrication conditions on the workpiece. Recently, the diversification from CNC technologies approach to robot-based technologies have rapidly enhanced and the increasing demands of process automation for unmanned manufacturing fascinated many researchers in the field of on-line monitoring of machining processes. In view of this, extensive research work is captivating place worldwide in the area of on-line tool affects the tool life. Tool life is primary importance in material processing remaining to its direct effect on the surface quality of the machined apparent, its dimensional accuracy, and as a result of the economics of machining processes [1]. Therefore, methods for tool wear evaluation are crucial in view of the optimal utilization of tools.

Tool wear evaluation had been crucial topics in determining the tool life. In protecting the tool life, many researchers studied and evaluated the tool condition, mostly in turning and milling process. However, no studies have been carried out for the robot-based ISF process. The tool condition monitoring is intensively carried out in CNC turning and milling processes. In turning process, a tool condition monitoring strategy based on a large number of signal features in the rough turning, where the signal feature can be extracted from the time domain signals as well as from frequency domain transform and their wavelet coefficients (time-frequency domain) [2]. A cutting tool condition monitoring system for high speed turning operation by vibration and strain analysis and the experiments was developed for various cutting speeds, depths of cut and feed rates [3]. An acoustic emission sensor was utilized to assess the internal change of tool holder to monitor the cutting tool condition and a tri-axial accelerometer sensor demonstrates the external effect on tool state, and the root mean square (RMS) signals and Fast Fourier transform (FFT) are used to illustrate the output of sensors [4]. An attempt has been made to access capability and suitability of K-star classifier for tool condition monitoring by acquired vibration signals and extracted statistical features of single point cutting tool in turning machining [5]. The utilization of a sensor fusion system that consists of vibration sensor and force based measurement system was attempted [6]. The results show that the combination of force and vibrations enhanced the accuracy of tool wear prediction. The tool condition monitoring in the micro-turning of aluminum alloy of AA 6061 using multiple sensors such as an acoustic emission (AE), accelerometer and cutting force dynamometer also was conducted [7]. The acquired signals were analyzed in time domain, frequency domain and discrete wavelet transformation (DWT) techniques.

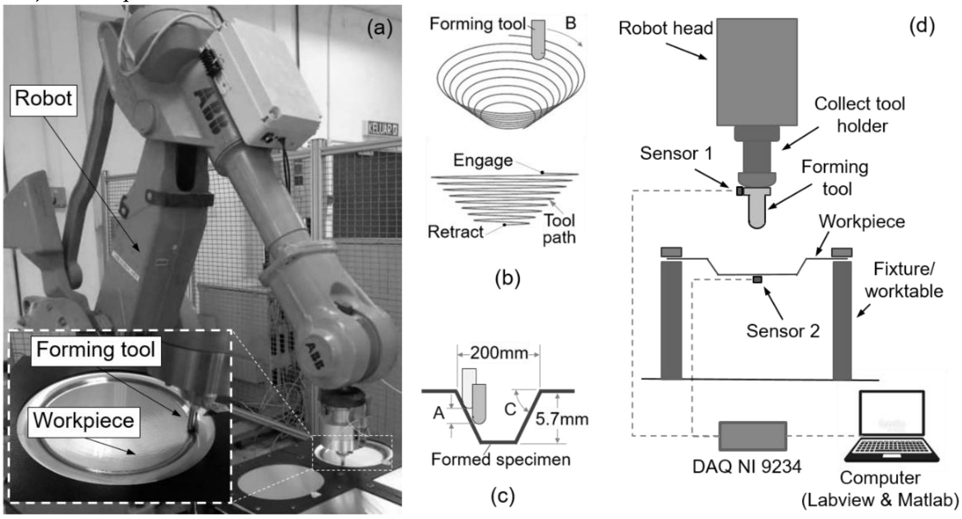

Figure 1. (a) Experimental setup, (b) helical tool path, (c) truncated cone shape of formed workpiece, (d) integration of components in data acquisition system

In milling processes, tool condition monitoring is widely investigated either using vibration or force sensor. The performance of clustering methods on high speed end milling experimental data which the clustering methods was applied to wavelet features of force and vibration signals to illustrate the results repeatability was demonstrated [8]. The paper also reveals the novelty of showing the reliableness of using vibration signal rather than force signals. Multiple sensors such as force, vibration, acoustic emission, and spindle power sensor for the time and frequency domain data were tested in designing multi-sensor fusion-based tool condition monitoring and the results showed that it can significantly improve the accuracy of the tool condition classification [9]. The research of tool condition monitoring based on original and demodulated signals measurements of a vibration generated by a cutting process in milling was make an attempt and this was being approached by monitoring spindle vibration using an accelerometer [10]. A reconfigurable system (consists of data acquisition system and hardware signal processing unit) to detect and indicate online and in real time for the cutting tool conditions in high speed face milling process has been presented [11]. The setting of the band-pass filter was based on the vibration characteristic patterns of the machining tests performed under different cutting tool conditions and the results show that 100% detection and indication of the tool condition. A cost-effective, wireless communication enabled, multi-sensor based tool condition monitoring system has been developed using Taguchi method [12]. The experiment employed three types of sensors to monitor vibration, cutting force and energy consumption profiles of CNC milling machine. The study on minimize tool vibration using a tool with such low rigidity and obtain good workpiece surface quality and long tool lives was being a challenged [13]. This was carried out by milling experiments on hardened AISI H13 using integral and indexable insert tools with different tool overhangs and different diameters. An extracted significant features of the cutting tool vibration signals from the sensor and transformed it into singular spectrum analysis (SSA) vibration signal form also has been investigated [14].

In this present work, an attempt has been made to analyze the vibration signals collected through accelerometer sensors in robot-based ISF for evaluating the tool condition and surface quality of formed workpiece. The paper is organized as follows: Section 1 covers the background and motivation of this work. In Section II, the experimental setup and feature extraction are explained. Then, the evaluation of tool wear and surface quality based on vibration signals in robot-based ISF are described in Section III. Finally, the paper concludes with a summary of this study in Section IV.

II. EXPERIMENTAL WORK

In this study, the SUS 316 stainless steel with 0.5 mm thickness was used as workpiece. The forming tool used in this experiments was fabricated from AISI D2 tool steel with a hemi-spherical tip of 10 mm in diameter. The experimental work was performed using a forming tool, which integrated with a six degree-of-freedom industrial robot as shown in Figure 1(a). The forming tool was held by a standard collect tool holder that attached to the robot head. The robot has a boundless movement ability and appropriate for completion a continuous-path controlled programme. The continuous-path movement of robot was channelled using robot teach pendant, which the sequence of forming points was defined to the robot in teach mode. The blank holder is fixed vertically on the worktable. The tool path used was helical tool path (Figure 1(b)) and the experiments has been conducted to produce the shape profile, which is a truncated cone with a diameter 200 mm and a depth of approximately to 5.7 mm as shown in Figure 1(c).

The main process parameters were step size, A (0.3 mm), robot speed, B (150 mm/s) and wall angle, C (45°). In this study, the step size is the vertical movement of the tool. Robot speed is referred as feed rate, while the step size is the vertical movement of the tool. Wall angle was manipulated by controlling the step of the tool along, the length or width, and radius of the truncated cone. Since the lubrication in SPIF process is necessary to reduce friction between forming tool and formed sheet metal in the forming area, the lubrication of synthetic oil with grade of SAE 15W-40 was used.

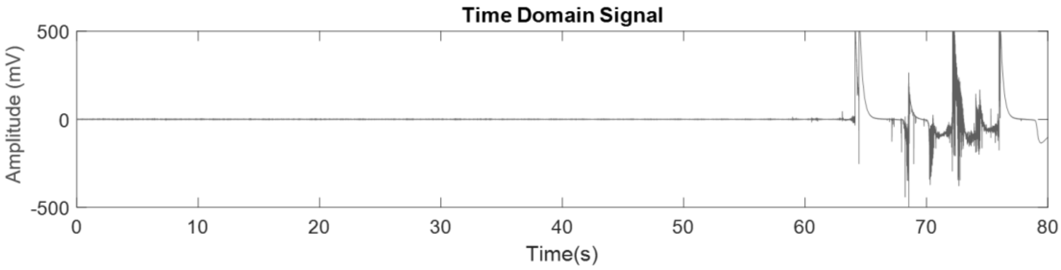

Figure 2. Pattern of vibration signal amplitude for forming tool

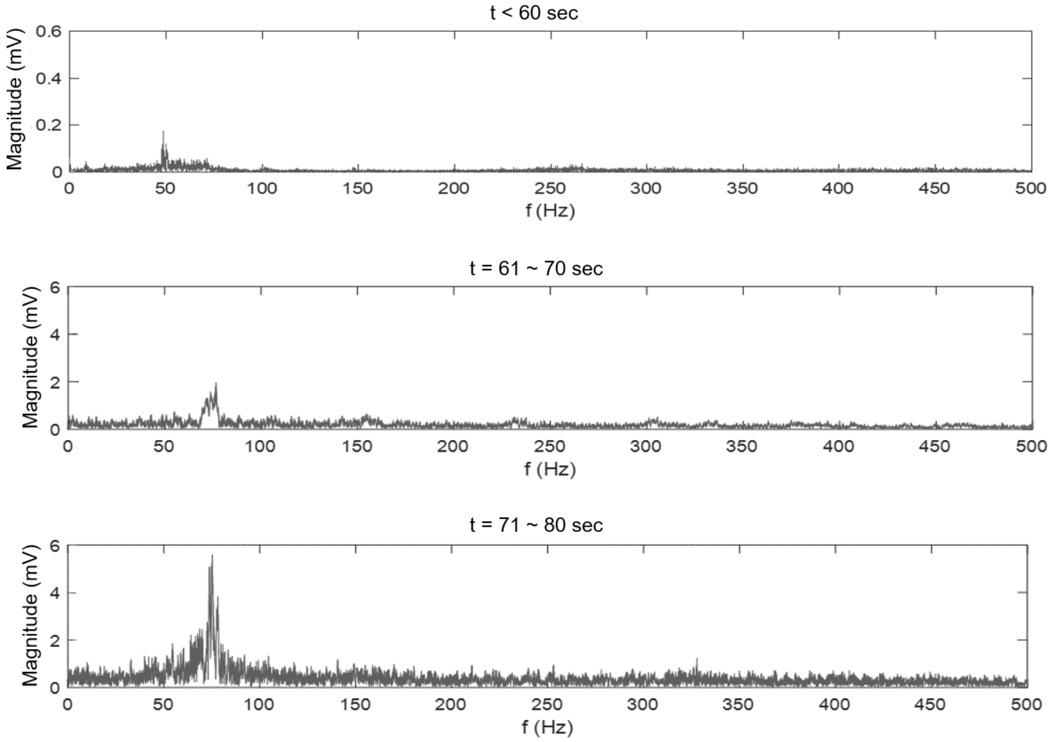

Figure 3. Vibration magnitude with frequency domain signal for forming tool

The schematic diagram of components integration with data acquisition system is shown in Figure 1(d). The vibration signal data was collected by two accelerometer sensors, which embedded on forming tool and bottom surface of the workpiece. The frequency range of both accelerometer sensors is between 50 to 400 kHz. The data acquisition module (NI 9234) was used as an analogue module for sampling an analogue signal from sensor input and digitized with signal noise reduction by passing the signal via a low-pass-filter and then logged by employing LabVIEW software. A computer program was written to capture and display this accelerator sensor vibration signals in the time domain in the routine of real time. Furthermore, the time-domain data of vibration can be quantified in statistical approach in terms of the values as Fast Fourier Transform (FFT). The FFT computation algorithm was incorporated in the computer program to extract the vibration propensity in the frequency domain.

After the robot-based ISF process, the forming tool was observed and the area of tool wear was measured using a digital microscope that integrated with measurement system (Lasso measurement). Lasso measurement is a measurement tool for freehand tracing a selection outline around an image. As tracing the image from digital camera, the perimeter (mm) and area (mm^2) of the selection outline are calculated automatically. In addition, the surface roughness of workpiece was measured at three different locations per workpiece and the mean roughness values of surface roughness were calculated.

III. RESULTS AND DISCUSSION

A. Forming Tool Evaluation

Figure 2 shows the vibrations signal in time-domain data from accelerometer sensors at forming tool to measure the vibration values in robot-based ISF process. The benchmark signal data is determined by the amplitude signal that produced by the accelerometer sensor. The higher amplitude of vibration shows the tool is worn out and not performing appropriately. The amplitude values before 60 sec is sustain

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below 10 mV, which showing less vibration, and the vibration suddenly rise up to 498.2 mV at 64 sec.

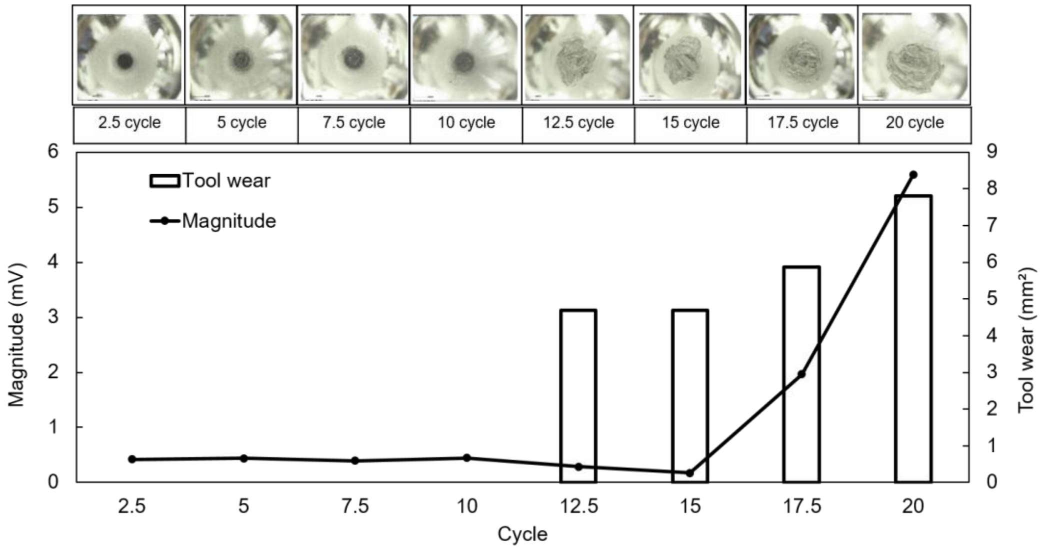

Figure 4. FFT results and wear values with tool wear evaluation

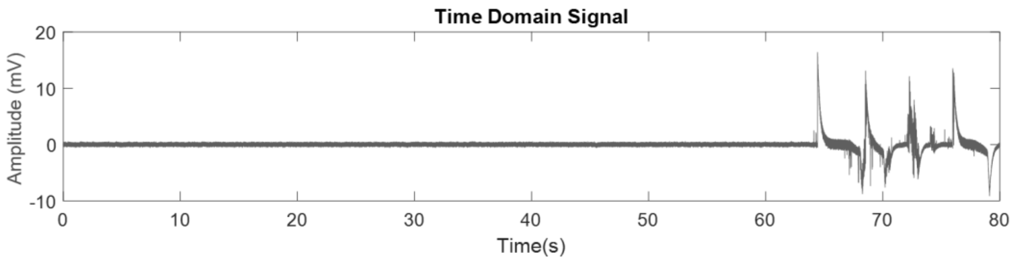

Figure 5. Pattern of vibration signal amplitude for workpiece

The increasing of the vibrations after 64 sec shows that the forming tool becoming worn and lose ability to perform the ISF process. Based on the tool condition, the vibration signal magnitude presents different features in the frequency domain as shown in Figure 3. The harmonic frequency is consistent at 48.55 Hz in the ISF process below than 60 sec. For duration after 61 sec, when the tool wear is fully developed, the harmonic frequency has shifted from 48.55 Hz to 76.75 Hz. This shift can be attributable to the fact that the friction between the worn forming tool and the formed workpiece [15, 16]. Also, it can be noted that the increment of vibration magnitude at the forming tool is according to the tool wear condition.

Figure 4 shows the evaluation of tool wear in physical and the FFT results based on the cycle of the forming process. One cycle represents the forming tool to complete a helical continuous-path movement in 360^0 position from starting point. The FFT value for every 2.5 cycles which is equivalent to 10 seconds was recorded to relate with tool wear evaluation at the same cycle points. It can be observed that the good condition of forming tool is produced during cycles up to 10 cycles (40 sec) with magnitude between 0.3-0.5 mV. It can be seen clearly after 17.5 cycles (70 sec), the magnitude drastically increases to more than 1.0 mV and significantly increase the dimension of wear on the forming tool. From the results, it can be noted that two phases of tool wear condition can be than categorized based on the vibration signal. The first phase of partial-wear condition is categorized with FFT value lower than FFT value of non-worn out forming tool. While the second phase of full-wear condition is characterised by extremely high FFT value. Figure 4 also indicates the relationship between tool wear and FFT values. At good condition (i.e. up to 10 cycles), the forming tool can sustain the tool profile as unaffected forming tool. The wear is started appeared on the forming tool at partial-wear condition before the wear rises at full-wear condition and directly affect to workpiece quality. It is clearly shows the trend of forming tool from good condition until wear condition using vibration can be used to detect the condition of the forming tool.

B. Workpiece Evaluation

In addition, the forming tool wear also can be associated with vibration signal of workpiece as shown in Figure 5. This vibration signal was gathered by using accelerator sensor that embedded under the workpiece. Lower vibration occurs before 60 sec and the amplitude values is maintaining 3 mV, however at 64 sec the vibration amplitude rises to 18 mV, and its indicates that the workpiece has been scratched. The increasing of the vibrations shows that the surface roughness on workpiece also developed scratched. Based on the workpiece surface roughness trend, the vibration signal magnitude also presents different features in the frequency domain as shown in Figure 6. The harmonic frequency is consistent at 50.26 Hz below 60 sec of the process. For duration after 61 sec, when the surface roughness is increased, the harmonic frequency has shifted to 110.13 Hz. Similar with tool wear results, this shift may be the effect of the friction force between the worn forming tool and the formed workpiece.

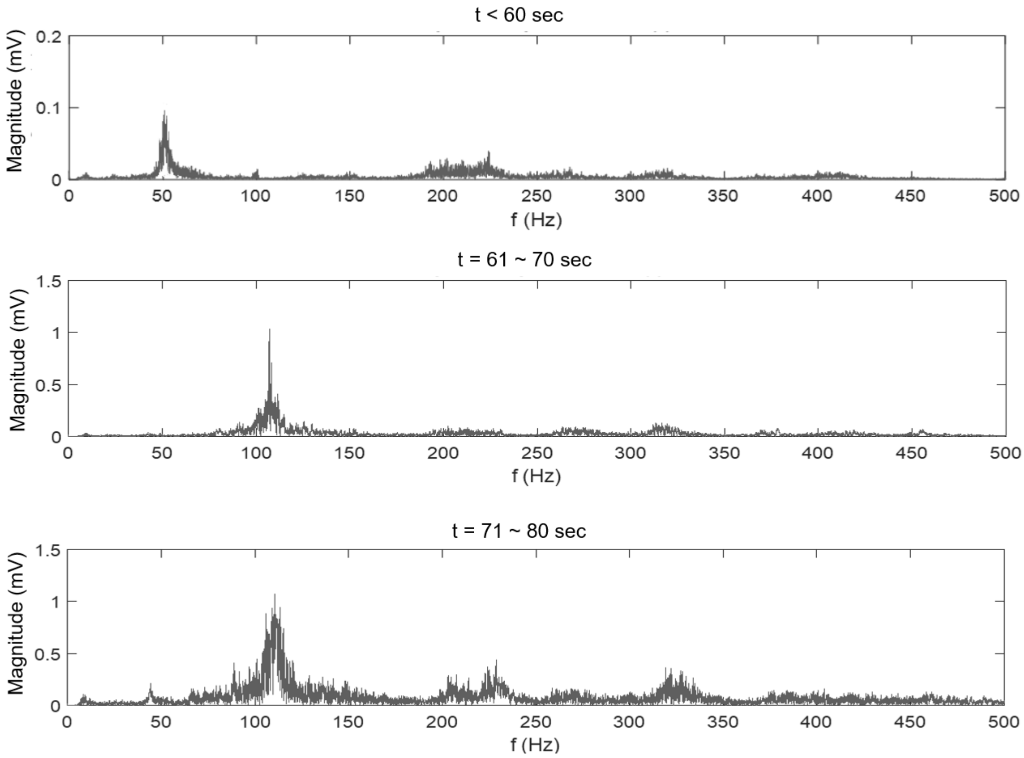

Figure 6. Vibration magnitude with frequency domain signal for workpiece

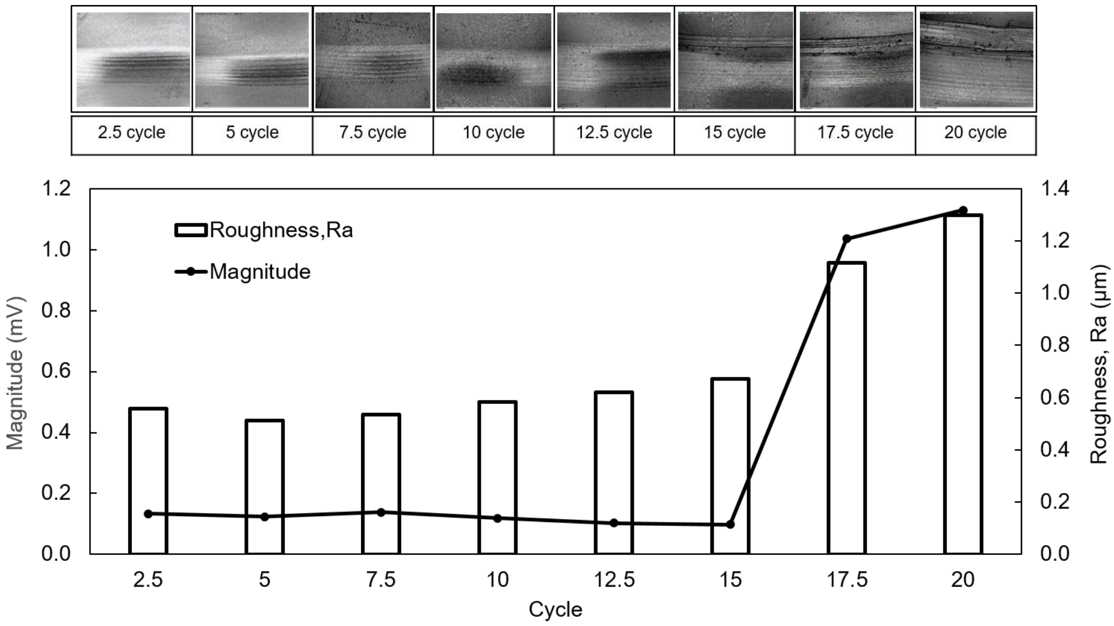

Figure 7. FFT results and surface roughness values for workpiece

Also, it can be noted this consequently raises the vibration magnitude at the formed workpiece is according to the surface roughness condition. This indicates that the correlation between tool wear and contacted surface on workpiece can be used as pattern recognition for tool condition monitoring using vibration signal.

Figure 7 shows the roughness evolution of contacted surface with forming tool on formed workpiece. The results showed that even the partial-wear condition starts to occur at 12.5 cycle of the ISF process, the surface roughness still remain low (below 1 µm), same as the formed workpiece contacted with good condition of forming tool. The surface roughness increases at 17.5 cycle onwards in the ISF process as the forming tool condition become worn-out in these cycles. In other words, with the increasing in depth of the ISF process, the scratched became worst and the vibration magnitude is found to be increasing with machining time increases, which may be due to the effect of the friction build

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ISSN: 0193-4120 Page No. 121- 126

up between forming tool and workpiece. This result also indicated that the contacted surface of formed workpiece is correlated with tool wear and vibration as shown in Figure 4 and shows a good agreement with those obtained in [17].

IV. CONCLUSION

The evaluation of forming tool condition and relationship with process performance on robot-based ISF of SUS 316 stainless steel by analyzing the vibration signal were experimentally investigated. The tool condition can be characterized into three categories namely good, partial-wear and full-wear conditions. The vibration magnitude increased with the increase of tool wear and subsequently affects on the surface quality of formed workpiece. In addition, the shifting of harmonic frequency also determines the effect of friction generated by axial contact between forming tool and the workpiece. Thus, the tool condition could be identified as the increasing of vibration amplitude which represents the forming tool become dull and reduce the product quality. The vibration signal also can be used to understand the tool condition stage and to determine the friction occurs between tool-workpiece. In future work, this pattern recognition can be used to monitor the tool condition for achieving the industrial demand by reducing the process cost and standardizing the product quality.

ACKNOWLEDGMENT

The authors would like to acknowledge the Universiti Putra Malaysia for financial support under the Putra Grant (GP-IPS/2016/9503100).

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