Robotic Grinding for Surface Repair

Mohammed Sufian and Xun Chen[0000-0003-2547-9022]

General Engineering Research Institute, Liverpool John Moores University, Byrom Street, Liverpool L33AF, United Kingdom.
Moe.sufian@hotmail.com, x.chen@ljmu.ac.uk

Abstract
Robotic grinding is considered as an alternative machining towards an efficient and intelligent machining of components due to its flexibility, intelligence and cost efficiency, particularly in comparison with the current mainstream manufacturing modes such as CNC machines. The advances in robotic grinding during the past years aims to solve problems of precision machining in small scale surfaces and other emphasizes on the efficient machining of large-scale surfaces. In this work, a method was investigated to improve surface repair accuracy by eliminating the workpiece datum error by directly engaging the grinding wheel. In fact, the proposed method uses acoustic emission sensing technique to detect grinding contact so as to estimate correct reference datum. Process variables based on machining parameters such as depth of cut, wheel speed, feed speed, dressing condition and system time constant is used to as a key parameter for controlling the robot to conduct the grinding process. The geometrical relationship and machining precision level developed has reached an accuracy level of 30μm and error is been controlled by considering the process variables such as depth of cut, wheel speed, feed speed, dressing condition and system time constant which is the key for controlling the robot to conduct grinding process .The recorded data provide a significant evidence to support the viability of implementing a 6-axis robotic system for various grinding applications, combining more quality and critical surface finishing practices, and an increased focus on the size and form of generated components**.**.

Keywords: Robot Grinding, Datum Identification, Error Compensation

1. Introduction

Robotic grinding produces a significant challenge due to its flexibility and accuracy particularly in comparison with the current mainstream manufacturing methods such as the use of CNC machines. For example, the precision concerns related to measurement area associated of the workpiece is crucial due to the geometric error of the surface of the component. It is an efficient machining process due its flexibility, cost efficiency and intelligence. They have the ability to create an enormous amount of cutting cycles which makes it flexible to machine or repair parts.

The challenge in measuring the accuracy control is that it is difficult to accurately measure the actual position of the robot when locating the workpiece which tends to provide failure to the algorithm matching the machining purposes causing incorrect values, profile errors and distribution problems [1]

In general, the geometrical accuracy of the machined product mainly depends on the kinematics of the machine, location of workpiece and tool location [2]. The geometric errors influence the location and orientation of the location of the workpiece and lead to misalignments of the workpiece. Researchers have proposed different methods based on error models, these models focus on the position and posture in relation to the joints of the robot. For example, Xiong et.al discussed the inner force distribution and load capacity of fixtures as well as the contact forces [3]. Marin and Ferreria discussed the impact of error on the location of geometry and tolerance of the workpiece [4]. Both concluded that the designed models need to have a direct relationship to achieve the required accuracy & the precision using a robot.

However, when repairing a surface on a component using a robot, it is difficult to obtain information of the without building a relationship between the workpiece and the robot. Establishing such a relation mode involves multi-sensor data in combination with the robot motion, which provide the necessary action guide to avoid any system errors caused by improper sensor resolution and installation [5]. Therefore, it is necessary to put forward robot motion control strategies which are suitable for collaborative machining and develop collaborative control software to realize the task allocation and interference avoidance.

This paper presents a method for damaged surface repair by combining welding and grinding operations. Welding is used to recover lost the material and grinding is used to reconstruct the functional surface with an adaptive strategy. Such a strategy will allow grinding cycle to achieve the required surface finish in a minimum machining time for the best economic efficiency

2. Contact Registration for Workpiece Datum

A contact registration is a procedure used to position and tolerate an object in the robot work envelop to create a reference system for geometrical position measurement. The traditional method used in many robotic applications to determine the workpiece datum is mainly using CMM (Coordinate measuring machine) touch prob. The inspection procedure is dependent on the dimension of the workpiece. However, the type of tools for probing may also be different from one to another too. For example, sensors or dial gauge method can be used to detect the surface of the workpiece to obtain the tool offset. Serval researchers has approached different methodologies to define a datum. For example, Jin and Jiyong developed a mathematical algorithm using three different coordinate systems to find a reference point to the workpiece to try to eliminate the influence error based on 3D measurements [6]. Chaiprapat and Rujikietgumjorn developed a model to predict the geometrical variation of the workpiece surface and datum features at a given workpiece [7]. Khondaygan analyzed errors in the workpiece–fixture–cutting tool system, he proposed to a relationship between the locating errors and their sources [8]. Lizarralde et.al presented a simulation software tool to facilitate grinding machine to achieve stable conditions [9].

Given the fact that the force control may cause machining errors. Pan and Zhang highlighted a control method based on compensations of deflections and adaptive material removal rate [10]. Bisu et.al. used a frequency-based method to measure the dynamic response of the robot when cutting at designated points, his method was not directly involved to machining path [11]. Zaghbani et.al have collected the cutting forces signals and vibrations in order to find a reliable dynamic stability machining with respect to spindle speed [12]. Zhao et.al investigated the effects of grain sizes, contact force, linear velocity and feed rate on the surface roughness in abrasive belt grinding of aviation blades by analyzing the response of surface [13]. Dumas et.al evaluated joint stiffness based on consideration of translational and rotational displacement of the robot end effector at a given force and torque, they concluded that joint stiffness values can be used for motion planning to optimize robot machining process but results were not validated making it un-reliable to use [14]

However, by establishing the geometrical relationship between reference datum and probe point of measurement, the error level of datum accuracy could be assessed based on the repeatability where the repeatable points are detected on the surface of the workpiece to assist the robot to define the reference point on the workpiece. In this work the acoustic emission sensor is used to provide real-time feedback to the robot system to monitor and control the detection process using the robot tool tip to define the reference point by eliminating the errors existed between the grinding wheel and conventional measuring prober

3. Theoretical Modeling

A theoretical model based on repeatability measurement is established to define the workpiece datum. The actual datum position of the workpiece can be estimated based on multiple points collected from the surface of the workpiece through a vector model to minimise the error measurement between the real and nominal datum. Through this model, the actual position of the workpiece is estimated and error could be compensated by applying suitable machining strategy.

A common formula of a plane in space can be presented as:

$$\mathbf{aX_i + bY_i + cZ_i + d = \varepsilon_i \;\; for\ i, \ldots.n} \qquad (1)$$

Considering the measurement errors ε, the measured points on plane should satisfy:

$$\mathbf{aX + bY + cZ + d = 0} \qquad (2)$$

As for variables **X**, **Y** and **Z** are coordinates taken from the different point of the surface of the plane on the block, **a**, **b**, **c** and **d** are constants that defines the plane position, and ε_i is the geometrical error.

$$\mathbf{Z_i = b_0 + b_1X_i + b_2Y_i + \varepsilon_i \text{ for } i, \ldots, n} \tag{3}$$

where $b_0 = -d/c$, $b_1 = -a/c$ and $b_2 = -b/c$. By defining $\mathbf{Z} = (Z_1, Z_2, \ldots, Z_n)'$, $\mathbf{B} = (b_1, b_2, \ldots, b_n)'$, $\boldsymbol{\varepsilon} = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n)'$

The geometrical error function becomes

$$\mathbf{Z} = \mathbf{BX} + \boldsymbol{\varepsilon} \tag{4}$$

Having established the error in each plane, the plane equation can be derived based on random points selected on the surface of each plane. For example, equation 5 below reflects the surface equation for the XY plane.

$$\mathbf{Z = d + (aX) + (bY)} \tag{5}$$

Note that the plane value, XY in the above case, is now reflective of any given point within the total XY plane. Consequently, transposition of the surface equation above, to find the constant 'd', yields the axis equation for the square. As shown in Equation 6 below.

$$\begin{aligned} d_1 &= (a_1X) + (b_1Y) - Z \\ d_2 &= (a_2X) + (c_2Z) - Y \\ d_3 &= (b_3Y) + (c_3Z) - X \end{aligned} \tag{6}$$

In three-dimensional space and integration of the variables and constants specified for each plane, the datum point X_0, Y_0, Z_0 of the robot work envelope can be established by solving equation 6 and be arranged accordingly to determine error values of each plane.

$$[\mathbf{E}] = [\mathbf{A_0}] + [\mathbf{A}][\boldsymbol{\alpha}] \tag{7}$$

Where $\mathbf{A_0}$ denotes the origin points, **A** represents the points developed from the axial equations and $\boldsymbol{\alpha}$ is the results generated in the repeatability testing for each plane

The transition angle can be corrected through vector models to compensate the transitional error of the datum point as shown in Fig. 1. The existence error between the real datum and nominal datum of the workpiece can be estimated and implemented into the robot accordingly. The datum is corrected through vector models to compensate the error and define the actual position of the workpiece to start grinding.

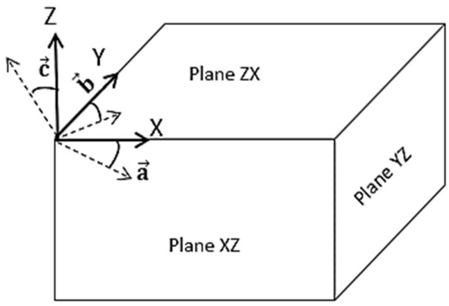

Fig.1: Transition angle correction for constructed geometry

$$\begin{aligned}
&\textit{Transition Angle } \vec{a} = \pm\left(\tan^{-1}\left(\frac{\Delta Y}{\Delta L_x}\right)\right)+\left(\tan^{-1}\left(\frac{\Delta Z}{\Delta L_x}\right)\right)\\
&\textit{Transition Angle } \vec{b} = \pm\left(\tan^{-1}\left(\frac{\Delta X}{\Delta L_Y}\right)\right)+\left(\tan^{-1}\left(\frac{\Delta Z}{\Delta L_Y}\right)\right)\\
&\textit{Transition Angle } \vec{c} = \pm\left(\tan^{-1}\left(\frac{\Delta Y}{\Delta L_Z}\right)\right)+\left(\tan^{-1}\left(\frac{\Delta X}{\Delta L_Z}\right)\right)
\end{aligned} \tag{8}$$

Where:

ΔX, ΔY, ΔZ = Repeatability Values

L_x , L_y , L_x = Distance between each detection point.

4. Accuracy Improvement with Robotic Grinding

The contact state between the work and the cutting tool presents a challenge to the robot compliance due to the difficulties in accurate modelling of force control. When machining such components, it is difficult to obtain information without building a relationship between the workpiece and the robot. This machining mode involve multi sensor data combination to allow the robot motion to provide the necessary outputs to avoid any error development. Therefore, is necessary to put forward robot motion control strategies which are suitable for collaborative machining and develop collaborative control software to realize the task allocation and interference avoidance.

However, the existing force and position control in robotic grinding aims to reduce the surface roughness of parts and pays less attention to the accuracy of form and position. The selection of the optimum grinding cycle parameters depends on the knowledge of deflections performance of the cycle. Therefore, to compensate the effect of deflections during grinding, it is essential to observe the robot compliance performance in relation to robot grinding infeed and sparkling within the cycle. As the magnitude of the grinding force changes with material removal rate and grinding wheel surface condition, it is often necessary to set a conservative operation conditions to perform grinding [15]. This means that most grinding cycles are not optimized for minimum cycle time and take longer time than required.

To improve grinding performance, the system time constant is a good measure of compliance of the grinding system. The time constant is the combined effect of the system compliance and the grinding forces during deflection between the machine and workpiece. The compliance represents the rate of deflection per unit force which depends on the geometrical factors of the workpiece as well as the grinding wheel and material properties. In this experiment, the time constant is used to allow for a more consistent control of spark out time during grinding as shown in the equation below:

$$T = T_0 . e^{-\frac{t}{\tau}} \tag{9}$$

where **T** being the remaining stock, **T_0** being the initial stock, **t** is the contact time and **τ** is the time constant estimated of the grinding system. It is important to determine the number of infeed and spark-outs for each grinding pass. The selection of the optimum grinding cycle parameters depends on the knowledge of deflections performance of the cycle. Therefore, to compensate the effect of deflections during grinding, it is essential to include a spark-out period to give us an idea of the infeed rates employed within the cycle to give more flexibility of the part, grinding wheel and the machine. In this experiment, the time constant is used to allow for a more consistent control of spark out time during grinding removal.

The grinding cycle model is started by taking into consideration the infeed stage as the first step, after that, the spark-out cycle is implemented to remove as the residual stock. As shown in Fig. 2, the amount of deformation is proportional to the normal forces and the real depth of cut during the grinding pass. Where:

$$F_n \propto \delta' \tag{10}$$

$$F_n \propto \varepsilon = F_n \propto \delta \tag{11}$$

$$\varepsilon \propto \delta \tag{12}$$

From hooks law relationship the stiffness (k) is introduced;

$$k\varepsilon \propto \delta \tag{13}$$

$$\varepsilon = \frac{1}{k}\ \delta \tag{14}$$

Therefore,

$$\varepsilon = \alpha\,\delta \tag{15}$$

Where α is the coefficient of deformation and 1/k is the stiffness. In the spark out stage, the residual stock continues to be removed until the wheel is retracted as shown in figure 5-7 were the grinding wheel is in contact with the workpiece. If the real depth of cut is $\boldsymbol{\delta}$ it should theoretically be cut to that position, but due to elastic deformation of the process system, it is elastically deformed due to the tip of the tool and the workpiece and only cuts to $\boldsymbol{\delta}'$. However, the infeed cycle can now be designed by taking into account the number of grinding strokes needed to reach the real depth of cut as shown in Fig.2.

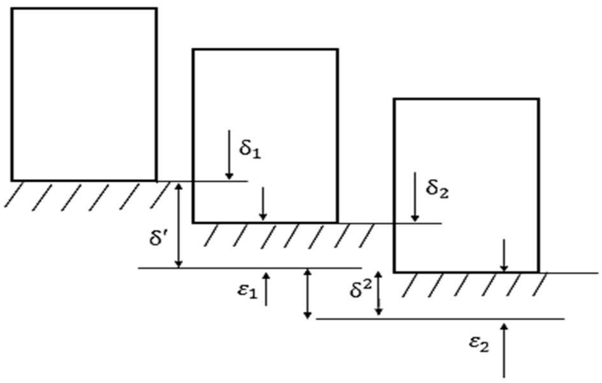

Fig.2: Infeed Process

If the theoretical depth of cut is δ', the elastic defamation amount per stoke is $\varepsilon_1, \varepsilon_2$ .... the real depth of cut is as follows:

$$\delta_1 = \delta' - \varepsilon_1 \tag{16}$$

Second stroke

$$\delta_2 = 2\delta' - \delta_1 - \varepsilon_2 \tag{17}$$

Where = $\delta_1 = \delta' - \varepsilon_1$

$$\delta_2 = 2\delta' - \left(\delta' - \varepsilon_1\right) - \varepsilon_2 = \delta' + \varepsilon_1 - \varepsilon_2 \tag{18}$$

$$\delta_i = \delta' + \varepsilon_{i-1} - \varepsilon_i \tag{19}$$

Where, **i** is more number of infeed in the cycle

Therefore,

$$\varepsilon_1 = \alpha\,\delta_1 \ldots\ldots\ldots \varepsilon_i = \alpha\delta_i \tag{20}$$

$$\delta_1 = \delta' - \alpha\,\delta_1 \quad (21)$$

$$\delta' = \delta_1(1+\alpha) \quad (22)$$

$$\delta_1 = \frac{1}{1+\alpha}\delta'$$

Carrying over from previous feed, Therefore,

$$\delta_i = \left[1 - \left(\frac{\alpha}{1+\alpha}\right)^i\right]\delta \quad (23)$$

Where:

$\frac{\alpha}{1+\alpha}$ = Infeed Ratio

However, the overall actual depth of cut is normally smaller than the total theoretical depth of cut, so the required dimensional accuracy is not achieved. Therefore, it is necessary to carry out the spark-out cleaning and gradually eliminate the residual deformation to achieve the required finish: For spark-out process shown in Fig.3 below

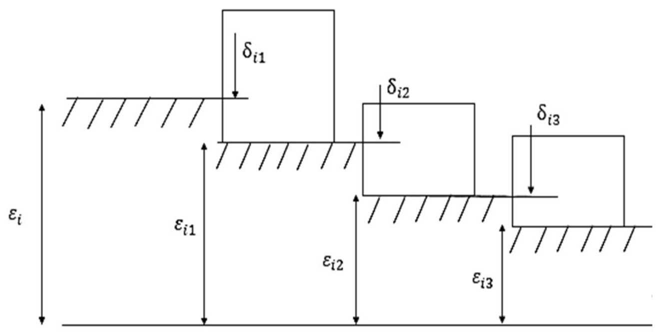

Fig.3: Spark-out process

$$\delta_{1i} = \varepsilon_1 - \varepsilon_{1i} \quad (24)$$

$$\delta_{ni} = \varepsilon_n - \varepsilon_{in(n-1)} \quad (25)$$

Where:

ε_{1i} = first spark out deformation

δ_{1i} = first spark out depth of cut

$$\varepsilon_i = \alpha\ \delta_i \ldots\ldots\ldots\ \varepsilon_{in} = \alpha\ \delta_{in} \tag{26}$$

Substituting into Equation 5-12:

$$\delta_{i1} = \frac{\alpha}{1+\alpha}\delta_1 \tag{27}$$

$$\delta_{in} = \left(\frac{\alpha}{1+\alpha}\right)^n \delta_i \tag{28}$$

Bringing the infeed stroke

$$\delta_i = \left(\frac{\alpha}{1+\alpha}\right)^n \left[1-\left(\frac{\alpha}{1+\alpha}\right)^i\right]\delta' \tag{29}$$

As the focus is on improving the accuracy of the robot to perform repair grinding. The level of error relative to its response is defined by measuring various locations on workpiece surface and implementing a mathematical model to generate a relationship between the workpiece and the cutting tool to predict the datum reference point and associated error. The datum is then corrected according to the robot position to provide a reliable and accurate grinding movement. By establishing the geometrical relationship between reference datum and the robot tool, a grinding theoretical model is developed to perform grinding for reconstruction of the surface to achieve a smooth surface finish. The optimum grinding cycle behavior depends on the knowledge of deflections between the grinding wheel and the workpiece resulting from the grinding force and system stiffness. Therefore, to compensate the effect of deflections during grinding, it is essential to observe the number of in-feeds and spark-outs within the cycle.

Finally, the theoretical model developed in this section provides a clear step to obtain the experimental process. The empirical model provides a strategy for repair that can achieve the maximum workpiece quality, minimum machining time and economic efficiency by making a selective adaptation strategy and chosen parameter selection.

5. Experimental Setup

A KUKA KR16 robot was used in this investigation. Throughout the planning phase of the experiments, some control variables for the robot is determined to the robot. The control variables are presented in Table 1, which lists related information including robot moving speed, payload, work envelope location, motion type.

Table 1. Robot Control Variables.

Control Variables	Normal Range	Setting
Working Speed	0 – 2 m/s	0.005 m/s
Spindle Speed	0-2500 rpm	2500 rpm
Robot Payload	0 – 16 kg	16kg
Grinding wheel load	0-200g	160g
Workspace location	0 – 1610mm	4 points within workspace
Motion type	Discrete	Point to point, Linear

The acoustic emission (AE) sensor used to assist the user to directly engage the grinding wheel to the workpiece to minimize the effect of error between the tool and the workpiece. The AE sensor is capable of generating feedback by sensing the position of the workpiece in relation to the tip of the tool on the robot which makes it one of the most promising processes for detection and monitoring methods. Average AE signal characteristics are shown in table 2. The effect of signal characteristics was not investigated in this work, as the aim of using the AE sensors is to detect the contact of workpiece and provide a real-time feedback to the robot controller.

Table 2. A.E Average Signal Detection

Detection Time (s)	Amplitude (V)	RMS	Energy (J)	Peak Frequency (Hz)
0.65124	34.2475	0.0042	93.1427	58.1562

At the point of contact between the workpiece and the robot tool tip, an analog signal provides a visual reference indicating the tool is contacted with the workpiece. At this stage, the interrupt command is declared in the robot software and the points are saved accordingly in the system. The sphere grinding tool is set at a 45° angle due to avoid zero cutting speed during operations. Fig. 4 below shows a general overview of the experimental set up.

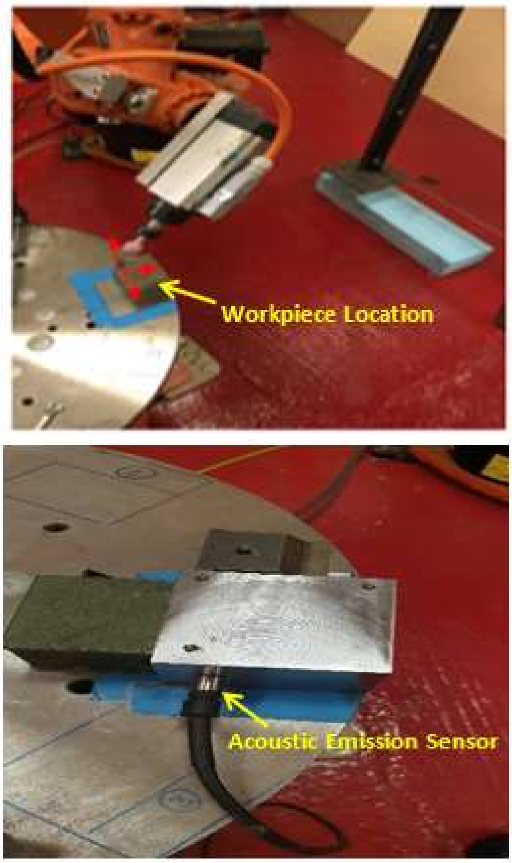

Fig.4: (a)Workpiece location, (b)Acoustic emission sensor Experimental Setup

5.1 Datum Measurement Setup

One of the challenges in robotic machining is the setup of workpiece datum in relation to the robot origin datum. The traditional methods used in robotic applications is mainly using a touch probe as used on a CMM (Coordinate measuring machine). The proposed work aims to define the datum by using a mathematical algorithm which aims to eliminate the influence of geometrical error which is the key for controlling the robot to conduct grinding process. The error level could be assessed based on the repeatability measurements and defined measuring points for full plane inspection. For correct implementation of the mathematical model, a full inspection of the plane is carried out by detecting four points on each plane surface to obtain the accuracy error level. The accuracy level is assessed based on the repeatability measurements of the relative datum position between workpiece and the cutting tool. After that, the mathematical model is used to predict the real datum point and then modified accordingly to the robot tool position. The identified workpiece datum will act as the reference point to perform the grinding operation. Fig.5 illustrates a 3D model of the three surfaces of the block used for detection.

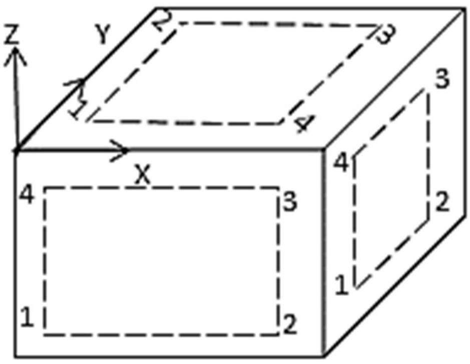

Fig. 5: Measurements points of detection

5.2 Repair Grinding Setup

Weld at random positions is created so that the model can be scanned to generate the required a tool path to be implemented with the robot to perform the grinding operation. This is a general way to perform repair engineering were small welding zones is created on the workpiece and restored to its original shape by grinding as shown in Fig. 6.

The operating parameters such as spindle speed, feed rate were kept constant and depth of cut is set to 0.3mm for roughing. Within the finishing process the depth of cut of is set to 0.1mm that is the minimum setting of the robot. During these stages, the material continues to be removed from the workpiece and monitored by the acoustic emission sensor to give feedback to the operator of material removal. The theoretical model developed based on system time constant is used to predict the material removal in roughing, finishing and sparking process to achieve high accuracy level. The cycle has been divided into three mains stages 1) roughing 2) finishing and 3) Sparking as shown in Fig. 7 schematic diagram below.

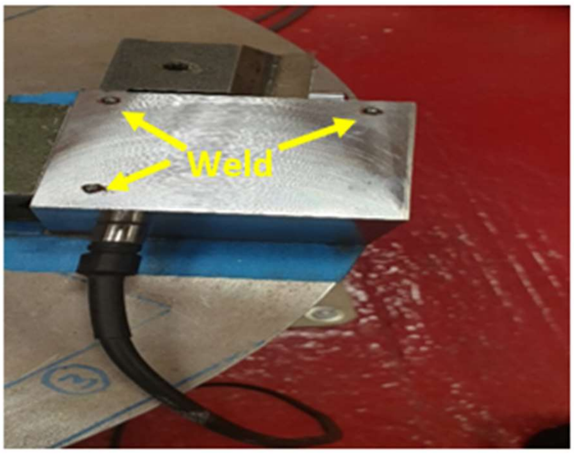

Fig.6: Weld Locations at ZX Plane

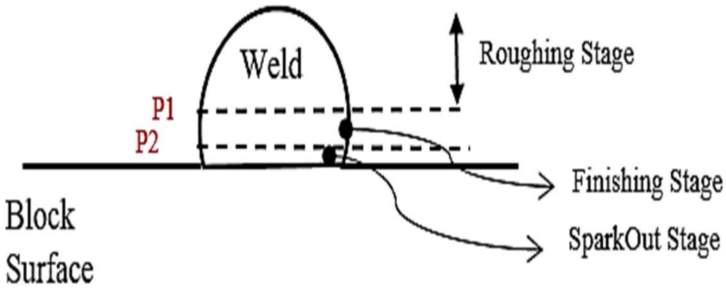

Fig.7: Grinding Cycle schematic view

6. Results and Discussions

An AE sensor used to monitor and measure the points by directly engaging grinding wheel to the workpiece to eliminate the effect of error between the tool and the workpiece. This is done by registering multiple points in each surface of the block under an operational speed of 0.005m/s which is the minimum infeed the robot can achieve. The result in table 3 show all points within number of repeatable times which shows that the use of acoustic emission sensor was useful for accuracy detection purposes.

The procedure is assessed based on repeatability were points are detected on each surface of the block to identify the geometric error and datum reference. Hence, the error model is developed towards the collected data to closely observe the datum point. This is done by visualizing the performance of robot repeatability and deriving a mathematical model for error compensation to locate the geometry datum points which proves the reliability and compatibility of using the acoustic emission sensor by engaging the tool into the workpiece.

Table 3. Robot Control Variables.

No. of Detection Times	Measurement of coordinates under 0.01m/s		
	Plane XY	**Plane YZ**	**Plane ZX**
1	-10.84361	-13.3375	-12.5153
2	-10.85271	-13.35154	-12.5264
3	-10.8525	-13.35482	-12.5157
4	-10.85291	-13.35384	-12.5157
5	-10.85113	-13.34399	-12.5161
6	-10.88352	-13.347548	-12.5143
7	-10.85952	-13.347558	-12.5145
8	-10.85952	-13.357548	-12.5148
9	-10.88552	-13.357948	-12.5151
10	-10.87589	-13.35848	-12.5149

After that, the datum is aligned directly to the robot which aims to increase the accuracy of the grinding processes. According to results, the mathematical error accuracy achieved is **30µm**. Based on repeatability measurements of the relative positions between workpiece and robot datum the mathematical model predicted datum points as

Workpiece Datum Coordinates:

$X_0 = 12.7302$

$Y_0 = 13.2228$

$Z_0 = 13.6362$

Datum Correction Trajectories

$$\vec{a} = i + 0.01432\ j + 0.00397\ k$$
$$\vec{b} = -0.01230i + j \mp 0.00201\ k$$
$$\vec{c} = -0.01054i + 0.008401j + k$$
$$Tansition\ Angle\ \vec{\mathbf{a}} = \pm 0.066°$$
$$Transtion\ Angle\ \vec{\mathbf{b}} = \pm 0.059°$$
$$Transtion\ Angle\ \vec{\mathbf{c}} = \pm 0.053°$$

6.1 Grinding Cycle Control

During the roughing stage, the influence of the depth of cut has been used to calculate the coefficient of deformation **α** in the system which is proportional to the normal forces and the real depth of cut. The theoretical model suggests that the roughing stage requires a seven number of roughing cuts, two finishing cuts and two spark-out passes to achieve final surface with minimum residual error. These cuts need to be controlled in a way where the weld is completely removed from the surface of the block without making any damage to the workpiece. Fig.8 below demonstrates the achieved experimental and theoretical results.

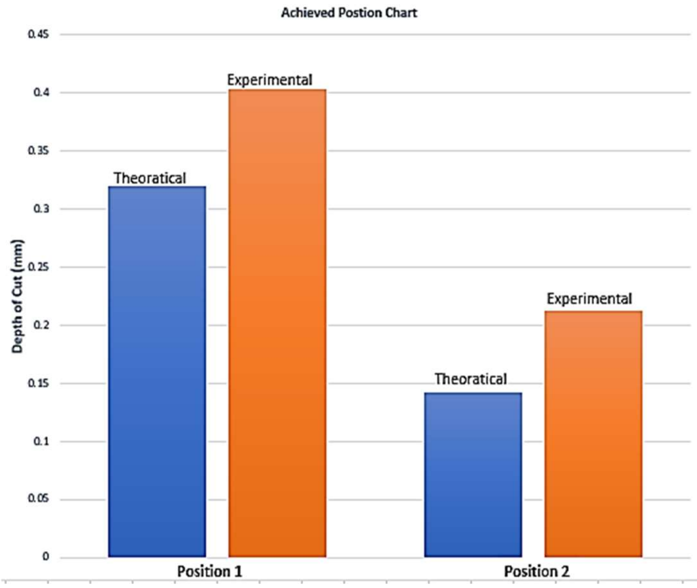

Fig.8: Achieved positions

In each stage, the robot tool cuts the material at a controlled depth of cut to ensure the material removal achieved. As can be seen from the results above, the theoretical and experimental stage at position 1 is achieved at 0.3199mm and 0.4030mm. Position 2 in finishing stage achieves 0.1421mm and 0.2130mm. The influence in the difference is related to the abrasive grains on the wheel in the contact area on the wheel due to the high forces affecting the wheel from stiffness of the joint causing residual stock on the workpiece. Due to the robot rigidity at a small area, the coefficient of deformation **α** value had an effect of the results because it was only calculated through the first cut. Also, the abrasive grains and the contact area were not taken into account in the calculations which also affects the contact stiffness of grinding wheel which is normally supported by the stiffness of single abrasive grain. It is known that the higher the surface roughness the lower the residual of workpiece and the higher the contact stiffness of grinding wheel. From such a viewpoint, this project aims to investigate the total grinding accuracy in order to perform grinding and not the effect of stiffness during grinding. Therefore, grinding operation was carried using a single grinding wheel and the residual stock removal of the workpiece was measured based on the depth of cut and calculations performed.

However, at the position at which the finishing stage ends, spark outs have to be carried out to ensure material is completely removed to smoothen up the surface. The advantage of spark-outs is to provide closer tolerances by removing the remaining stock, therefore a number of two spark outs have been made according to the theoretical model. A profile measurement is conducted to measure the weld area to observe how much residual material is left. The machine allows to capture the contour profiles of the boundary using a single probe to observe how much material is been removed from the surface.

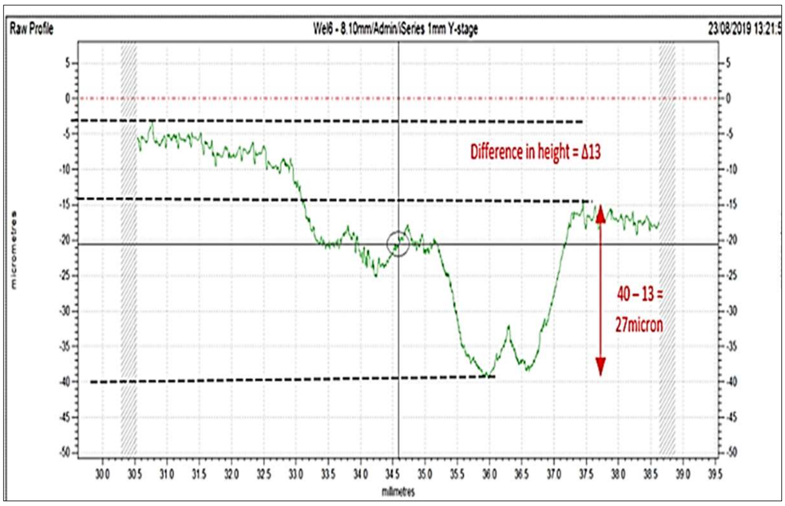

Fig.9: surface profile measurement area at ZX

The residual is approximate 30 microns below the surface level, this could be due to large forces generated in the wheel caused from the stiffness of the robot. Also, a small lip noticed due to the tool being lift of the surface of the block which is due to an error related to the dynamic behavior of the robot arm which mainly occurs from structural deformations, stiffness and robot compliance. The effect of these conditions is difficult to control because the maximum of depth of cut is limited to 0.1 mm and the angle between the grinding spindle axis and the surface tangent (usually 45°) overt the grinding process. This eventually causes errors between the tool and geometry resulting to unexpected material on the surface of the block. Preventing unwanted motions possess more challenging design problem, which can significantly affect the performance. However, The depth of cut achieved is approximately less than 30micron which validates the accuracy level achieved form method developed which proves it is efficient and could be used for repair engineering

7. Conclusions

Robotic grinding is an effective technique that could revolutionize the repair works in manufacturing industry. This work establishes a repair method to perform grinding using an articulated 6-axis robot. Through this method a geometrical relationship between workpiece reference datum and grinding wheel can be established and the error level is assessed based on the repeatability and defined measuring points on the surfaces of the workpiece. An optimum grinding cycle is designed by taking advantages of abrasive machining to support and guide the selection of infeed speed and number of passes required to verify the final grinding repair operation. This provides a suitable solution for precision material removal for repairing components in manufacturing and maintenance operations. The work concludes the following points:

- Based on repeatability measurements of the relative positions between workpiece and robot datum, the mathematical model developed is used to predict the workpiece datum. The geometrical datum error achieved is less than **30μm** which supports the process monitoring and control strategy to provide a reliable and accurate grinding movement using the robot.
- The developed grinding cycle has improved the machining repair accuracy to a level of **30μm.** The investigation considers the process variables such as depth of cut, wheel speed, feed speed, dressing condition and system time constant as a key variable in the design of the grinding cycle.

Finally, this work provides a suitable solution for precision measurement to repair components in manufacturing and maintenance operation using a robot in many industrial sectors. The main novelty of this work is defining the error accuracy by using the cutting tool as a probe in the robot system using acoustic emission monitoring technology that modifies robot commands accordingly. a mathematical model is developed for compensating machining errors in relation to its geometrical position by utilizing system relaxing technique that satisfies the need of eliminating the residual error during robot grinding.

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