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# Analysis of Contact Conditions based on Process Parameters in Robotic Abrasive Belt Grinding Using Dynamic Pressure Sensor

Vigneashwara Pandiyan  
School of Mechanical and Aerospace  
Engineering  
Nanyang Technological University  
Singapore, 639815.  
[vigneash002@e.ntu.edu.sg](mailto:vigneash002@e.ntu.edu.sg)

Gunasekaran Praveen  
School of Mechanical and Aerospace  
Engineering  
Nanyang Technological University  
Singapore, 639815.  
[PRAVEEN008@e.ntu.edu.sg](mailto:PRAVEEN008@e.ntu.edu.sg)

Tegoeh Tjahjowidodo  
School of Mechanical and Aerospace  
Engineering  
Nanyang Technological University  
Singapore, 639815.  
[TTEGOEH@ntu.edu.sg](mailto:TTEGOEH@ntu.edu.sg)

Tomi Wijaya  
Rolls-Royce@NTU Corporate Lab  
Nanyang Technological University  
Singapore, 639815.  
[TWijaya@ntu.edu.sg](mailto:TWijaya@ntu.edu.sg)

Wahyu Caesarendra  
Rolls-Royce@NTU Corporate Lab  
Nanyang Technological University  
Singapore, 639815.  
[WCAESARENDRA@ntu.edu.sg](mailto:WCAESARENDRA@ntu.edu.sg)

Bobby K Pappachan  
Rolls-Royce@NTU Corporate Lab  
Nanyang Technological University  
Singapore, 639815.  
[KBOBBY@ntu.edu.sg](mailto:KBOBBY@ntu.edu.sg)

**Abstract**— The material removal in complicated geometries is the principal objective for machining with compliant abrasive tools in aerospace industries. Realizing ideal material removal rates with fine tolerance in tertiary finishing process such as abrasive belt grinding is essential. This makes it fundamental to look in more detail at the process parameters/variables that affect the material removal rate. However, the relationship between the material removal rate and process parameters is not well understood. Previously, five parameters such as belt speed, feed, rubber hardness, grit size and force applied were studied in correspondence with the depth of cut, and it was found grit size plays a dominant role in the grinding process [1]. In this study, the influence of four parameters out the five parameters namely belt speed, feed, rubber hardness and force are investigated using a dynamic pressure sensor. Three level of input for each parameter was considered. Experimental trials were conducted by varying the levels of one parameter and maintaining a constant level for other three parameters. Based on the experimental trials performed using the dynamic pressure sensor, a correlation between the three levels considered for each parameter is identified based on the contact conditions. It was observed that pressure distribution based on the contact condition using the pressure sensor for the parameter considered followed the same results as predicted by ANOVA [1]. This research work describes a systematic approach to analyse process parameters based on contact conditions using a pressure sensor to understand material removal in a compliant abrasive belt grinding process.

**Keywords**— *Belt grinding, parameter analysis, material removal, Pressure film sensor*

## I. INTRODUCTION

In abrasive micromachining, material removal occurs due to the interaction of randomly oriented multipoint cutting edges and the workpiece material. Due to this undefined tooltip and negative rake angle, the specific energy is very high at the machining point. The grinding belt is made up of coated abrasives and is fastened around at least two rotating rubber contact wheels, which makes it a compliant tool as shown in Fig. 1. The soft contact rubber wheel enables this machining process to appropriately manufacture free-form surfaces due to its capability to adapt to the workpiece surface [2]. Abrasive belt grinding process is a form-adaptive

machining technique; this is due to the inherent flexibility of backing material in the abrasive belt and the hyperelastic property of polymer rubber contact wheels. The form adaptive characteristics make the abrasive belt to act as a compliant tool. One of the common example in industries where complaint tooling used is in tertiary components and localised error correction. Most of the parameters defining the abrasive belt grinding process are work material, grit size, grit hardness, grit orientation, the velocity of the belt, feed rate, contact wheel hardness, serration in the wheel, and applied force. The belt grinding process is highly nonlinear, and in the industry still based on empirical rules and experience of the operator [3, 4].

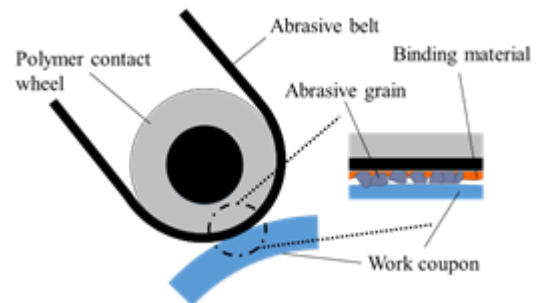


Fig. 1. Principle of belt grinding process.

A systematic approach for quantification of belt grinding parameters in such a dynamic process is reported previously in [1]. Influence of different levels from the individual belt grinding parameters such as RPM (m/min), feed rate (mm/sec), force (N) and hardness (Shore A) on the material removal has been depicted in Fig. 2. The main effects plot based on the signal to noise ratio (SN) with the concept 'the larger-the-better' is adopted. The results of the SN ratio for the four parameters at three levels shows that material removal rate increases with increasing RPM, force, hardness and decreases with increasing feed. The average contact pressure, the effective contact duration and the number of active grains in the contact are the most important parameters controlling the belt grinding process locally [5]. A three-dimensional numerical model is established to model the contact between the belt constituted by abrasive grains and the surface and to understand many tribological situations

[6]. The overall methodology of determining the material removal rate and predicting surface evolution was determined based on pressure distribution using pressure film sensors for compliant coated abrasive tool [7]. Experimental work on pressure distribution at the interface that influences the material removal process between contact grinding wheel and a workpiece has been studied comparing pressure film results and finite element analysis [8]. Understanding the contact pressure using FEA modelling is relatively complex because information on the physical property of workpiece, belt, polymer wheel, tool speed are difficult to obtain. Static pressure films have the inherent disadvantage of not capturing the pressure distribution in real time, which emphasises of using a sensor capable of capturing the pressure distribution based on contact conditions in real-time as discussed in this research. Only limited studies have focused on understanding the parametric effects affecting the contact conditions of the belt grinding process concerning pressure distribution or material removal. This work tries to bridge this gap.

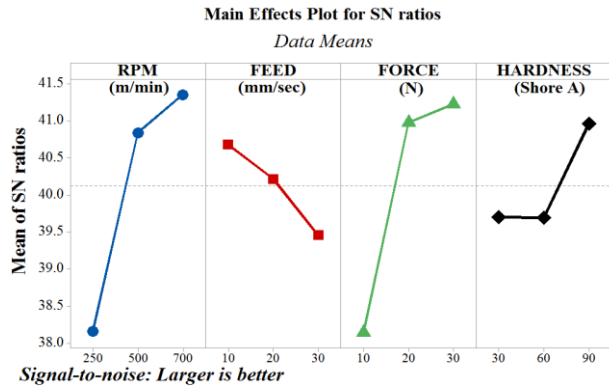


Fig. 2. Mean of SN ratio for selected process parameters [1].

The paper is organised as follows: an overview of abrasive belt grinding process and the problem statement is presented in Section I, followed the machining conditions, experimental setup in Section II. Results of the dynamic pressure sensor are summarised in Section III. Finally, the conclusions of this research work are reviewed in Section IV.

## II. EXPERIMENTAL SETUP AND TRIAL CONDITION

Pressure pad tests were conducted to study the relationship between parameters and pressure distribution during machining. The parameters such as RPM, feed rate, force and rubber hardness that influence the contact conditions were investigated. Three level of input for each parameter was considered. The parameters and their levels are listed in TABLE I. The experimental setup consists of the ABB robot, customised electric grinder, and pressure sensing system. The experimental trials were accomplished by fastening the belt grinder and an ABB 6660 multi-axis robot using a suitable fixture, as shown in Fig. 3. ATI force sensor was mounted to the ABB robots end-effector, and then the customised belt grinding tool was attached to the force sensor. ABB robot arm is used mainly for toolpath control and force control. Force control is mainly used for maintaining uniform contact along the whole toolpath. A constant contact force throughout the pressure sensing trials in the normal direction (Z-axis) was achieved by using a force sensor (ATI Omega 160). Uniform contact is realised by constraining tool centre point (machining end) interacting

with the surface normally, which is the current industrial practice employing highly automatic robotic arm manipulators.

TABLE I. BELT GRINDING PARAMETERS AND THEIR LEVELS

Parameter	Level		
	L1	L2	L3
RPM (m/min)	250	500	700
Feed (mm/sec)	10	20	30
Force (N)	10	20	30
Rubber hardness (Shore A)	30	60	90

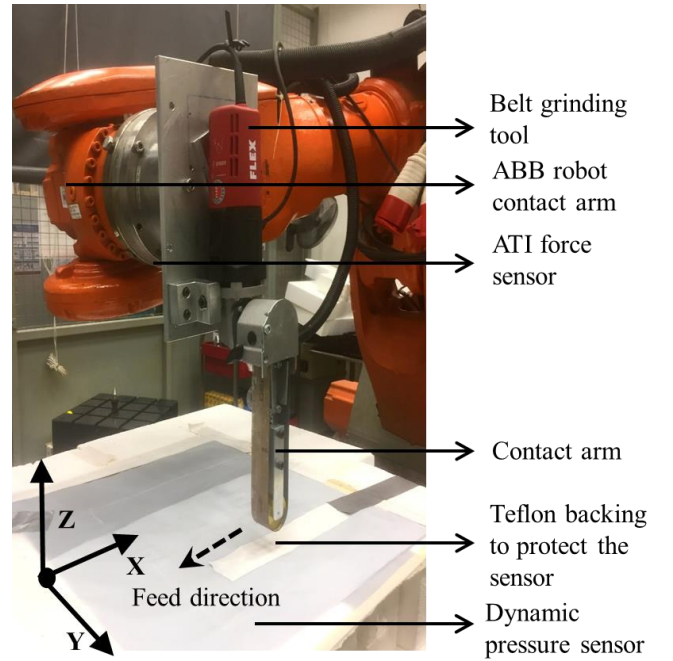


Fig. 3. Belt grinding setup

The X3 IX500:128.128.10 dynamic pressure sensor is used to measure the pressure distributions over a contact area during the experimental trials in real time. Pressure sensing measurement is made with a tough urethane cover with 16,384 sensing points with a 2.54mm pitch (resolution) [9]. The pressure sensor consists of a capacitive transducer comprising of two parallel plates that are separated by an air or dielectric medium. In a typical parallel plate capacitor, the distance between the two plates is fixed, but in variable capacitance transducers, the distance between the two plates is variable. The change in distance results in a resultant change in capacitance. The change in capacitance is directly related to the pressure applied to the capacitor. Multiple arrays of pressure sensing variable capacitors from input pulses are then signal conditioned into an image data. The pressure sensor has a spatial resolution of 2.54mm and has a sensing area of 32.5cm x 32.5cm. The working temperature range is between 10–40°C and has eight frames per second output with withstanding threshold as 30Bar pressure. The

pressure pad is put on the flat aluminium work coupon and secured to the surface to avoid displacement during the contact of the grinding wheel as shown in the Fig. 4. Extra care is taken by isolating the pressure pad contact with the worktable to avoid electronic interferences in the parallel plate capacitor due to metallic objects. The pressure pad sensor surface is protected using the Teflon sheet as the abrasive belt rotates at higher speed. Effect of the presence of Teflon sheet between the sensor and contact wheel on the pressure reading is negligible as sheet were of small thickness of 0.3mm and weighed less. The pressure data were recorded during the grinding experimental trials in real time and later retrieved for post analysis.

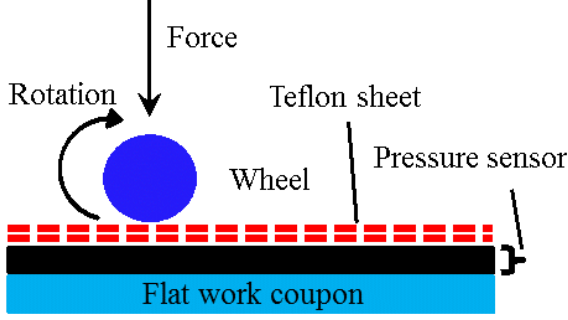


Fig. 4. Schematic diagram of the pressure sensor.

Trials were designed in such a way that one of the parameter to be studied is made variable while other three parameters are maintained at a constant value. Constant value for the remaining three parameters was taken from level 2 from the respective parameter.

TABLE II. DYNAMIC PRESSURE TEST INPUT CONDITIONS.

Trial	RPM (m/min)	Feed (mm/sec)	Force (N)	Hardness (Shore A)
Trial 1	250	20	20	60
Trial 2	500	20	20	60
Trial 3	700	20	20	60
Trial 4	500	10	20	60
Trial 5	500	20	20	60
Trial 6	500	30	20	60
Trial 7	500	20	10	60
Trial 8	500	20	20	60
Trial 9	500	20	30	60
Trial 10	500	20	20	60
Trial 11	500	20	20	30
Trial 12	500	20	20	90

First three trials have the RPM changed with a constant feed, force and hardness. Similar procedure is followed for feed, force, and hardness in subsequent trials. The experimental layout for finding the correlation between the

three levels considered for each individual parameter is identified based on the contact conditions is provided in TABLE II. Grit parameter was not considered for the dynamic pressure sensing test because of using grit may damage the pressure pad during operation. The working temperature range of the pressure sensor was between 10–40°C which is well below the temperature generated during the actual belt grinding process. Therefore, experiments were performed only with the backing material of the commercially available belt. The contribution of each parameter to the material removal based on the contact conditions and pressure distribution are analysed, and the same is explained in detail in the following Section 3.

### III. RESULTS AND ANALYSIS

The abrasive belt grinder used in the experimental trials had a contact thickness of 24mm for its contact wheel. Pressure distribution pattern obtained based on the trial from TABLE II. were not symmetric as result of low spatial resolution of the pressure sensor. The spatial resolution of the pressure sensor used in the experimental trials was around 2.54mm. It is evident that pressure distribution pattern obtained during the actual trials can be more or less represented using the proposed setup. Violin plot is also used to represent the change in density estimates of the pressure distribution for varying the levels of each parameter. Trials 1, 2 and 3 were used to correlate the relationship between the levels of RPM. Based on the RPM levels 250, 500 and 700 it was found that pressure distribution increased with increase in RPM as shown in Fig. 5.

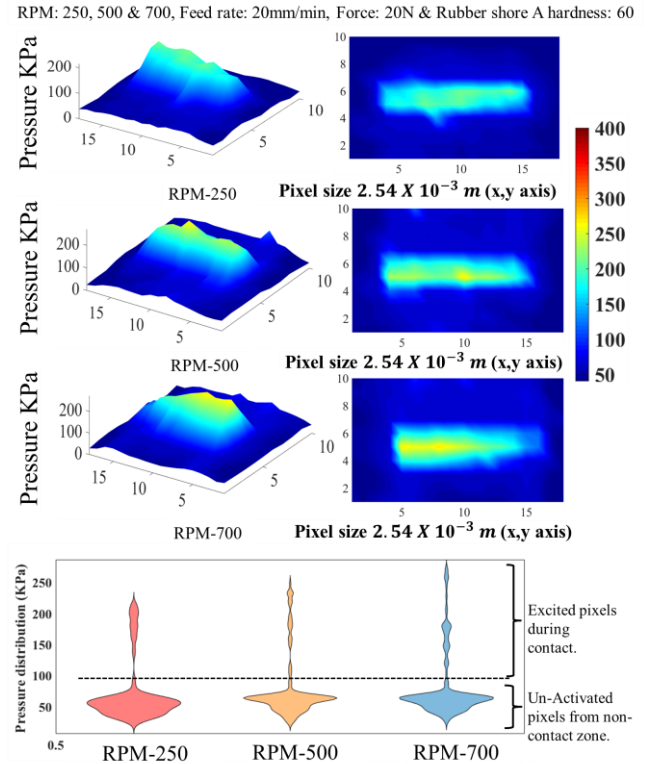


Fig. 5. 2D, 3D and violin plot comparison of pressure distribution with a change in RPM and constant rubber Shore A hardness, feed rate, force

The contact pressure intensifies when the number of the interactions between the polymer wheel and surface due to the rotation of the polymer wheel per unit time is maximized.

Pressure distribution results from trials 4, 5 and 6 were used to correlate the relationship between the levels of feed rate. Based on the feed rate levels 10mm/s, 20mm/s and 30mm/s it was found that pressure distribution decreased with increase in feed rate as shown in Fig. 6.

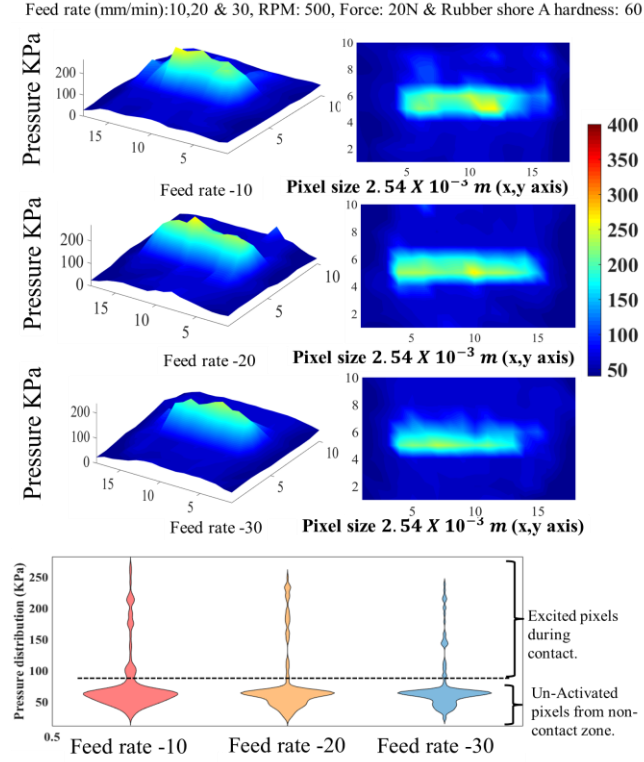


Fig. 6. 2D, 3D and violin plot comparison of pressure distribution with a change in applied feed rate and constant RPM, force, hardness

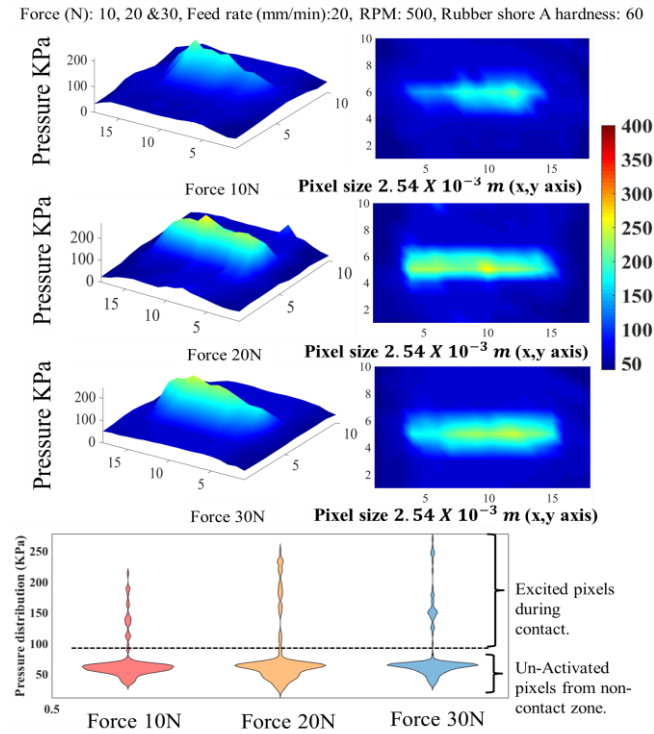


Fig. 7. 2D, 3D and violin plot comparison of pressure distribution with a change in applied force and constant RPM, feed rate, rubber Shore A hardness.

Contact pressure increases with a higher dwell time of interaction between the polymer wheel, and workpiece surface, i.e., contact pressure pattern is inversely proportional to the feed rate. Fig. 7 shows the pressure distribution variation in force with constant feed, force, and hardness as represented by Trials 7, 8 and 9.

10N has no significant impact on machining. In addition, the pressure exerted on the surface is very low compared to other 20N and 30N. Adequate force penetrates deeply into the workpiece to achieve grain-cutting depth resulting in high-pressure distribution proportional to applied force. From the visual analysis of Fig. 7, it was evident that pressure distribution increased with increase in force imparted. Analysing the 2D and 3D plots in Fig. 8 from experimental trials 10, 11 and 12 with varying the three levels of Shore A hardness; it was evident that pressure concentration increased with increase in hardness of the polymer wheel, but the distribution pattern area was observed to be inversely proportional. The pressure distribution pattern involving polymer wheel of Shore A hardness 30 with good compliance effect showed that pressure concentration per unit area was lesser but was distributed to a large area. Due to the very less compliance property of the contact wheel of Shore A 90 hardness, it was found that contact area was like a line contact and the pressure concentration per unit area was observed to be higher.

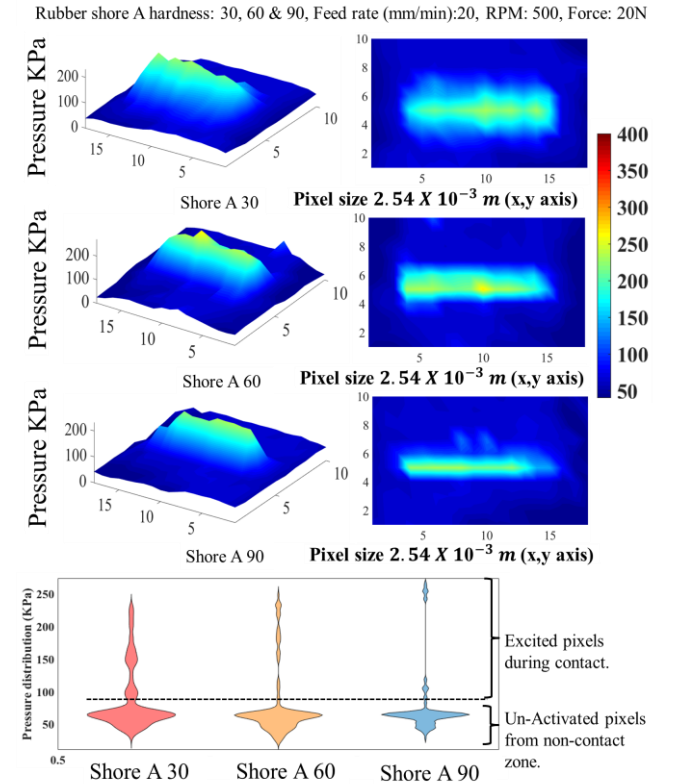


Fig. 8. 2D, 3D and violin plot comparison of pressure distribution with a change in rubber Shore A hardness and constant RPM, feed rate, force.

#### IV. CONCLUSION

A dynamic pressure sensor is used to determine pressure distribution caused by a compliant belt grinding tool for the understanding of material removal mechanism. The pressure sensor is also used to determine the pressure distributions

based on the contact conditions induced by different levels of each process parameters considered. It was observed that pressure distribution for each level in each parameter followed similar results as predicted by main effects plot using ANOVA [1]. Following conclusions were drawn from the investigation.

- It was found that pressure distribution increases with a higher dwell time of interaction between the contact wheel and workpiece surface, i.e., material removal, is inversely proportional to the feed-in rate.
- The penetration depth of the grinding wheel into the work coupon surface, i.e., the pressure distribution concentration increased with the amount of normal force imparted from 10N to 30N.
- Pressure distribution concentration on the contact surface was found to be inversely proportional to the hardness of the polymer wheel.
- Analysis of pressure distribution for three different RPM's of 250, 500 & 750; it is evident that material removal is directly proportional to the cutting speed (grinding rate) of the polymer contact wheel.

Understanding the dynamic pressure distribution will help to correlate interaction effect between the levels of process parameters to develop a prediction model for transient grinding conditions. Besides, contact condition and pressure distribution on complex geometries are also needed, and cross-interactions between each level of the different parameters are also to be studied to develop a comprehensive material removal model with soft computing techniques, which is in progress for further research.

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