Evaluating Thermo-Mechanical Stress Measured during Surface Grinding on a Sensor Integrated Workpiece Using COMSOL Multiphysics

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Abstract: By integrating sensors in a workpiece it is possible to characterize manufacturing processes like grinding, deep rolling and milling. For example: in-situ measurement of process parameters during a surface grinding process. But sensor is a foreign element to the material and can alter its properties by adding discontinuities to the homogeneity of the material. In such a case there will be discontinuities in the measurement signal as well and this can lead to a high order of measurement uncertainty or in accuracy. Additionally, the extent of measurement deviation may vary depending on how the sensors are embedded into the material. This paper presents the simulation of the thermo-mechanical stress measured on a sensor-integrated workpiece, '*sensorial steel',* during surface grinding and compares it with that on a *homogenous* workpiece that does not have sensors integrated to it. The simulation also includes how the measured stress differs based on the technique used to embed the sensors on the *sensorial steel* (soldered or glued) and in this way the foreign body effect of the sensor on the material can be determined.

Keywords: sensor integration in workpiece, in-situ measurement, grinding, FEM simulation, COMSOL

1. Introduction

Integration of sensors in different materials is of significant importance because integration makes it possible to take measurements inside the material. Integration of sensors in metals is of great interest in applications like structural health monitoring and in characterization of manufacturing processes. By integrating thin-film sensors on a workpiece, an intelligent 'Sensorial Workpiece' can be created which can help in characterizing manufacturing processes by measuring in-situ process parameters (force, temperature). In this paper, characterization of surface grinding process with a sensor integrated workpiece has been considered. Grinding is a finishing process hence, in-process monitoring will ensure enhancement of the work quality along with cost reduction [1]. But due to its abrasive and complex nature, it is difficult to take measurements during the process. Hence, sensors can be used for in-situ monitoring of the process. In such cases, embedding sensors directly in the workpiece material can provide useful information about process parameters through direct measurement of the physical quantities in the material and they can be monitored in real-time to control the process effectively. The integrated microsensors can also help in improving the surface quality of the workpiece. This idea of measuring in-situ process parameters to determine material modifications comes from a new concept of creating *Process Signatures* of manufacturing processes by correlating the loads occurring in a manufacturing process with the modifications made in the material [2]. It assumes that all manufacturing processes are driven by a certain combination of loads that act on the workpiece during machining. These loads (energy) can be broadly classified as thermal, mechanical and chemical loads. The single effect of these basic loads or a combination of these loads determines the properties of the machined workpiece and the basic loads remain the same in all different manufacturing process. Hence characterization of manufacturing processes to create *Process Signature* and determine surface and sub-surface material properties using a sensor integrated workpiece is attempted in the present work.

For integrating sensors in metals, there are two approaches: one is 'hybrid integration' where sensors are developed externally (mostly using silicon technology) and later embedded into the material and the other is 'a local build-up of the sensors' where the sensor is directly deposited using additive technology like thin-film deposition [3]. Reported literature on sensor integration in workpiece material is few. Choi, Datta et. al. developed strain gauges and thermocouples embedded in steel substrates using thin-film deposition technique [4]. The embedding was completed by electroplating a protective layer of Nickel on the thin-film sensors and this unit could be integrated into other metallic structures as required. Cheng et.al. presented strain gauges made of Palladium-wt. 13% Chromium (PdCr) alloy fabricated on stainless steel using thin film technology [5]. The system also consisted of a stack of three dielectric layers grown on the steel substrate before and after the deposition of strain gauges and the entire system was embedded using diffusion bonding. This was then used to test a vertical-end milling process. Another group developed an intelligent workpiece fabricating thin film thermocouples using silicon technology and later transferring them to Nickel substrates by electroplating for testing a welding process [6]. The Nickel-embedded microsensors were integrated into a copper workpiece using ultrasonic metal welding before testing it in an industrial environment.

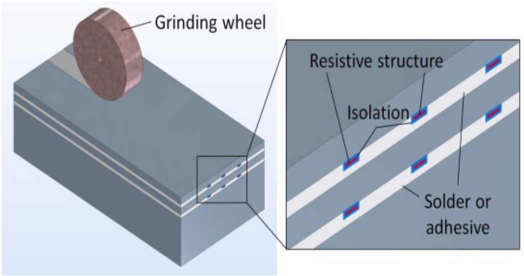

Figure 1: Schematic diagram showing the concept of 'sensorial workpiece' with integrated thin-films and the embedding technique

In the scope of this work, the aim is to integrate sensors in the workpiece material to characterize a grinding process as shown in Figure 1. Here, the sensors are fabricated by depositing thin-films of resistive structures on the surface of steel wafers using microfabrication technology. The steel wafers with the thin-film structures are then diced into individual units which form the 'sensorial inlay'. For completing the embedding process, the inlay is glued or hard soldered to a pre-machined groove on a bigger steel workpiece and this creates the 'sensorial steel' as shown in Figure 2. The steel wafer and the steel workpiece are made from the tempered steel: 42CrMo4 (AISI 4140)

However, due to integration a 'wound effect' is created in the material which alters its physical properties [3]. This causes discontinuities in the measurement signal and makes it inaccurate. Additionally, upon integration of sensors, an embedding layer is present due to which there is loss of energy transferred from the grinding process in to the material. This will also affect the stress measurements. Hence, in order to calibrate the measurements and to compare the results obtained when embedding a sensor using different sensor embedding technique, it is important to predetermine the error in measurement through FEM simulation and this is the motivation of the work presented in the paper.

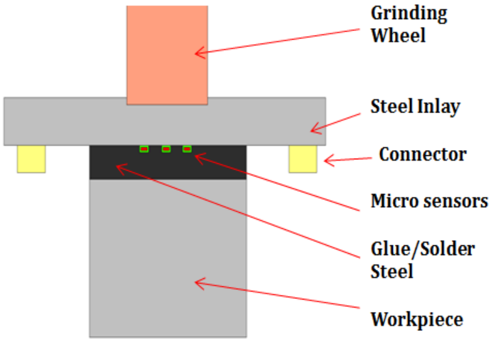

Figure 2: Cross-sectional view of the complete sensor-integrated workpiece

3. Use of COMSOL Multiphysics

Both mechanical and thermal simulation models of the grinding process have been built separately using COMSOL and later the models were coupled to show the combined mechanical and thermal effect on the workpiece.

The '*Structural Mechanics Module'* was used to analyze a 2D model of the workpiece. The geometry of the workpiece is shown in Figure 3. The homogenous workpiece without the integrated sensors consists of a rectangular block of steel with dimensions 100 mm x 18 mm and the sensorial workpiece consists of two steel blocks joined together with either a hard soldering layer or an adhesive layer of thickness 50 µm as shown in the figure.

For the workpiece material, the steel AISI 4340 was selected from the materials library and added to the geometry, a lead/tin alloy (60 Sn-40 Pb) was added as the soldering layer and PMMA as the glue. Since the senor film is very thin (200 nm) its effect has been neglected in the model.

To differentiate between the steel and the embedding layer, a *parametric sweep* function was used on two material properties: young's modulus and thermal expansion co-efficient of the steel and the solder/glue. Hence the assumption is that the steel, solder and glue differ only in these material properties.

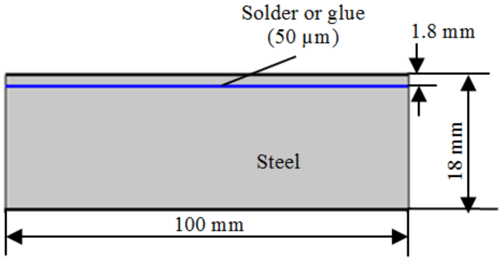

Figure 3: Geometry of the workpiece used in the model

For modelling the mechanical impact of grinding, the in-situ stress measured by the integrated sensors during the process has to be evaluated. This can be done by calculating the principal stresses on the free surface of the workpiece during one grinding feed. For a two-dimensional linear-elastic isotropic material with τ_{xy} as the shear stress, the maximum and minimum stress in x-y plane is given by [9]:

$$\sigma_{max,min} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} \quad (1)$$

Here σ_x gives the stress state in x-direction and σ_y gives the stress in y-direction. In COMSOL, this equation can be computed using the **'Solid Mechanics'** physics from the Structural Mechanics module using a stationary study.

As shown in Figure 4, a boundary load (force per unit length) was applied to the top surface of the workpiece. The load has a tangential component and a normal component in x and y directions respectively. The normal force is F_n = 450 N/m^2 and the tangential load is F_t = 1000 N/m^2. These values are taken from the real-time experiments done on a sensor integrated workpiece in a previous work [7]. The boundary on which the load is applied represents the grinding wheel and its length (l_g) is equal to the contact length of the grinding wheel given by the relation [8]:

$$l_g = \sqrt{a_c . d_s} \quad (2)$$

Here, a_c is the depth of cut and d_s is the diameter of the grinding wheel.

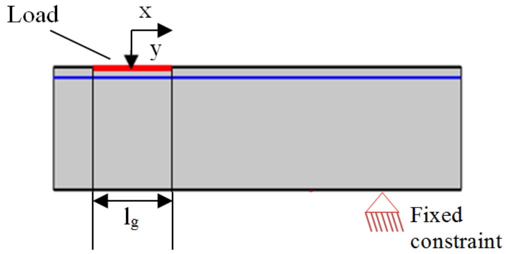

Figure 4: Boundary conditions used in the mechanical model. l_g is the contact length of the wheel

The contact length was roughly calculated as 6 mm using this equation and the parameters obtained from the previous grinding experiment [7]. The base surface of the workpiece is fixed on the work table and so a fixed constraint is applied at a point on the bottom surface of the geometry and rotation of the workpiece is prevented by a prescribed displacement in y direction on the bottom surface. The thickness of the workpiece is taken as 20 mm for the 2D assumption.

For the temperature model, the **'Heat Transfer in Solids'** module of COMSOL was used. The grinding process generates heat and the high temperature will influence the in-situ measurement of stress using thin-film strain sensors. Hence a thermal model of the grinding process was developed to study the effect of thermal stress on in-situ force measurement.

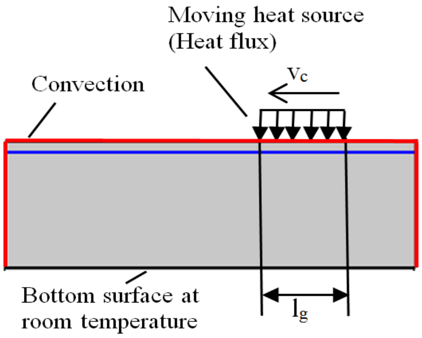

Figure 5: Boundary conditions used in the thermal model. v_c is the feed and l_g is the contact length

This is also a 2D model where a moving heat source is assumed to be the grinding wheel that is moving at a speed of v_c= 35 m/s [7] as shown in Figure 5. This kind of model for the thermal effect of grinding was proposed by Jaeger [8] and the heat source is quantified by the total heat flux entering the workpiece per unit time. The heat flux entering the chips of removed material is neglected.

In the heat source, the heat flux remains constant along its length and this length is also equal to the contact length of the grinding wheel (l_g). The heat flux Q is estimated using the relation:

$$Q \quad = \quad \varepsilon\, P_c'' \qquad (3)$$

ε refers to the fraction of heat energy entering into the workpiece and P_c'' is the actual heat flux entering the workpiece, also known as the specific grinding power [10]. This value was already obtained from the previous grinding experiments. Neglecting the heat flux entering the chip, the percentage of heat flux entering the workpiece can be roughly estimated to be 80% of the total grinding energy. Hence, the previously calculated value of $P_c'' = 13.1\ \mathrm{W/mm^2}$ was used to compute the total heat flux entering the workpiece and that is 10.5 $\mathrm{W/mm^2}$.

The heat transfer model is considered as a time-dependent model and the total time for one grinding stroke is divided over 15 time frames (t = 0 - 15s). The heat flux flows inward through the top surface of the workpiece. The effect of the coolant fluid used in grinding is assumed here as a convective heat flux flowing outward through the top and side walls of the workpiece as shown in Figure 5. The heat transfer coefficient used was: h = 20 $\mathrm{W/m^2K}$. The bottom surface of the workpiece is considered to be at 20°C.

4. Results

The two-dimensional stress tensor in x-y plane is considered to be the actual stress measured by the integrated microsenors during experiments with the grinding process. The measured stress on the workpiece due to the mechanical effect of grinding only is shown in Figure 6. It can be seen that the stress is highest near the top surface of the workpiece and decreases along the depth of the workpiece. A deflection at 1.8 mm below the top surface can be seen in the workpiece that have integrated sensor inlays. This is due to the presence of the sensor inlay at that point which causes a 'wound effect' and introduces discontinuity in the measurement signal. The effect is higher in case of the workpiece with a glued sensor inlay as compared to that with a soldered inlay as can be seen in the figure. However, the important observation here is that the stress tensor remains in the same range of measurement in all three cases.

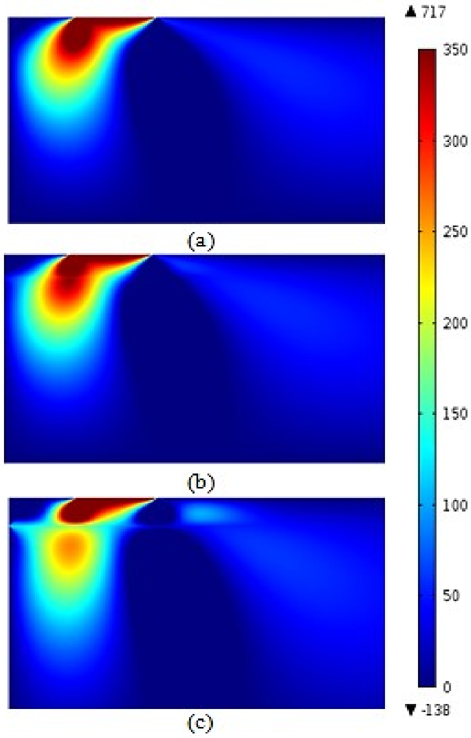

Figure 6: Result of the mechanical model showing 2-d plot of stress tensor ($\mathrm{N/m^2}$) in x-y plane in: a) homogenous workpiece without sensor inlays, b) workpiece with a soldered sensor inlay, c) workpiece with a glued sensor inlay

The comparison of the measurement signal can be better explained from the 1-D plot of the stress tensor over the depth of the workpiece as shown in Figure 7. Here a cross section has been made at a point on the 2-d plot and the variation of the stress tensor from the top surface to the bottom surface of all the three different workpiece is shown.

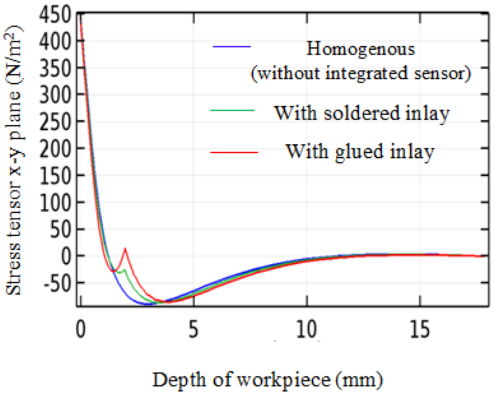

Figure 7: 1-D plot of the variation of stress tensor in x-y plane over the depth profile of the three workpiece in case of the mechanical model

In the thermal model, the temperature measured on the surface of the workpiece is evaluated. It is a time dependent model and hence the change in temperature at each time instant in the range from 0 to 15 seconds in one stroke of the grinding wheel is plotted. The temperature (in Kelvin) plot at time instant t =7s for the homogenous workpiece without integrated sensor inlays is shown in Figure 8.

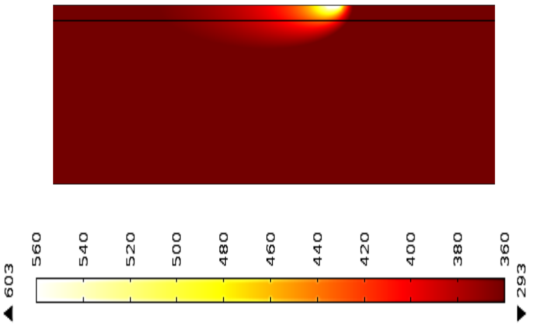

Figure 8: Temperature plot (Kelvin) at time t=7s for the homogenous workpiece

For modeling the grinding process it is necessary to consider both mechanical and thermal effects. Hence the individual models that have been computed were combined so that the measured stress has an influence of both mechanical and thermal stress. The built-in module ‘Thermal Stress’ in COMSOL has coupling parameters that can link Solid Mechanics and Heat Transfer models. This module was used to combine the individual models and to see the influence of temperature on the mechanical stress formed on the workpiece due to the grinding process. The mechanical model was stationary and the temperature model was time-dependent. The stress tensor in x-y plane was measured at the time instant t = 7s. At this time instant, it was assumed that the load was directly over the sensor and the boundary condition was changed accordingly. This is shown in Figure 9. The same 1-D plot of measured stress over the depth of the workpiece was created for this combined model as well and this is shown in Figure 10. Comparing figures 9 and 10 with figures 6 and 7, it can be seen that both curves have a difference in the stress-tensor showing that there is a significant influence of temperature on the measured stress though the range of measurement is almost comparable.

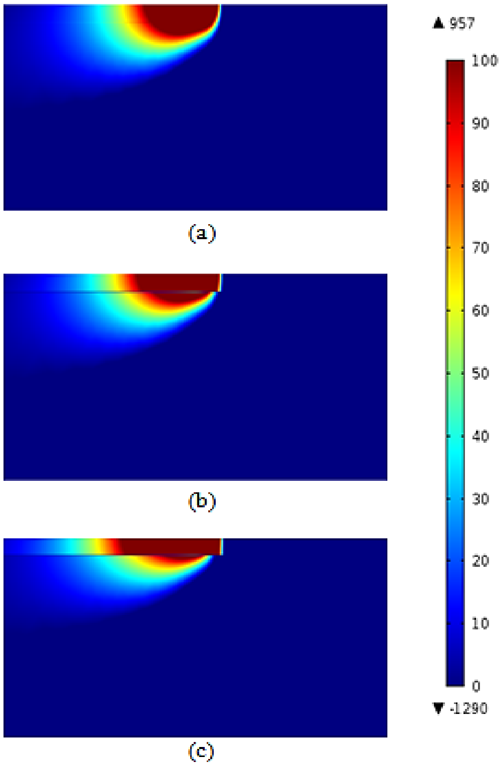

Figure 9: 2-D plot of stress tensor (N/m^2) in x-y plane for the combined mechanical and thermal model. The stress is measured in: a) homogenous workpiece without integrated sensor inlay, b) workpiece with soldered sensor inlay and c) workpiece with a glued inlay.

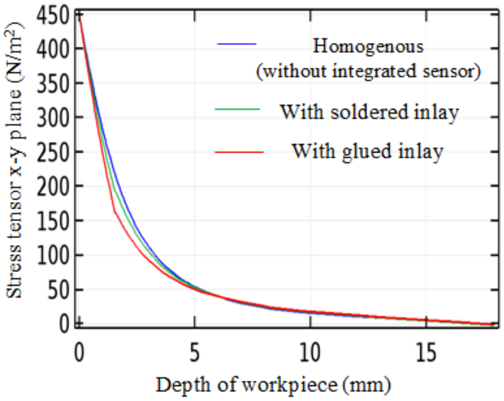

Figure 10: 1-D plot of the variation of stress tensor in x-y plane over the depth profile of the three workpiece in case of the combined mechanical and thermal model

5. Conclusions

By integrating thin-film sensors into a workpiece, it is possible to characterize abrasive manufacturing processes like grinding to evaluate surface properties or take in-situ process measurements. Due to integration there will be a disruption in the homogeneity of the material and there will be a disturbance in the measurement signal which will cause measurement uncertainty. But it will not alter the measurement signal quatatively. The extent to which the measured signal deviates from expected behavior also depends on the way the microsensors are embedded in the material. As shown in this work, the sensor inlay that is embedded into the workpiece using hard soldering has a lesser deviation than the inlay that is glued to the workpiece. Embedding by glue is simple and cost-efficient but it creates a larger measurement error. However, since the distortion of the signal is not very significant and the range of measurement is comparable to that of a homogenous workpiece, it is possible to calibrate the measurement signal and this can produce a reproducible effect. Hence glued inlays can be used as an alternate solution for embedding pre-fabricated microsensor inlays into materials.

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