World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:15, No:9, 2021

A Numerical Study of the Interaction between Residual Stress Profiles Induced by Quasi-Static Plastification

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***Abstract*—**One of the most relevant phenomena in manufacturing is the residual stress state development through the manufacturing chain. In most cases, the residual stresses have their origin in the heterogenous plastification produced by the processes. Although a few manufacturing processes have been successfully approached by numerical modeling, there is still lack of understanding on how these processes' interactions will affect the final stress state. The objective of this work is to analyze the effect of the grinding procedure on the residual stress state generated by a quasi-static indentation. The model consists in a simplified approach of shot peening, modeling four cases with variations in indenter size and force. This model was validated through topography, measured by optical 3D focus-variation. The indentation model configured with two loads was then exposed to two grinding procedures and the result was analyzed. It was observed that the grinding procedure will have a significant effect on the stress state.

***Keywords*—**Plasticity, residual stress, finite element method, manufacturing.

I. Introduction

THE development of methods for predicting manufacturing phenomena steadily grows due to their high potential to contribute to the component's performance. That relevance increases if mechanical parts are subject to combinations of residual stresses and complex loads. In this perspective, the interaction among shot peening and grinding has been under the spotlight because of its kinematics complexity, and due to its contribution to the final stress state. In this context, Klocke et al. [1] showed a deviation in residual stresses of almost 50% on the automotive gear industry, even with production parameters maintained constant. Therefore, to understand the residual stress variability, the manufacturing chain influence on the final stress state and the variation of these stresses between processes must be understood. An approach to this interaction is made in this study, where simplified models of a quasi-static cold work process interact with a grinding procedure. Therefore, the effect of the thermal-mechanical loads of grinding on the residual stress state of the indentation is observed.

II. Materials and Methods

A. Residual Stress Interaction

The main objective of this work is to observe the residual stress interaction. A model was developed where characteristic loads of two different manufacturing processes could be applied. This model captures the interaction between an indentation, simulating a cold work mechanical process, with a grinding model, applying the process in the order shown in Fig. 1.

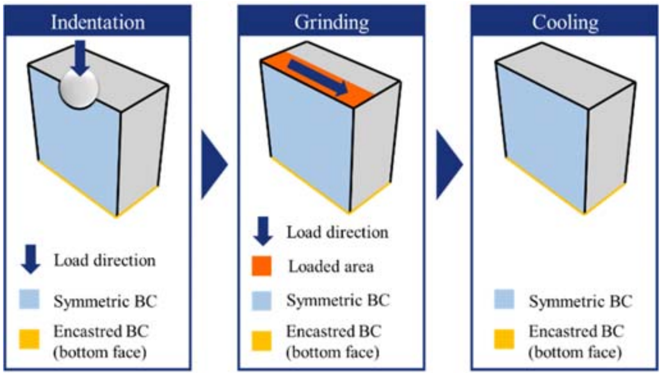

Fig. 1 Interaction scheme

B. Quasi-Static Indentation Model

The quasi-static indentation model was developed to replicate the plastic deformation occurring during a peening process using the principle that the kinetic energy of shot peening can be replaced by the strain energy applied in an indentation process [2]. Therefore, the quasi-static model was developed based on the Rockwell B load profile, Fig. 2, using the 1/16" and 1/8" indenters with the load varying from 125 kgf to 250 kgf.

The model was developed using a dynamic explicit solver of ABAQUS's CAE, due to its efficiency in modeling non-linear problems. When using a dynamic solver to compute a quasi-static model, the energy applied needs to be monitored, to assure that dynamic phenomena do not affect the final result.

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This work was partially financed by FAPESP (grant 2018/09251-0), CNPq (grant 310742/2020-0) and CAPES (grant 88887.465419/2019-00)

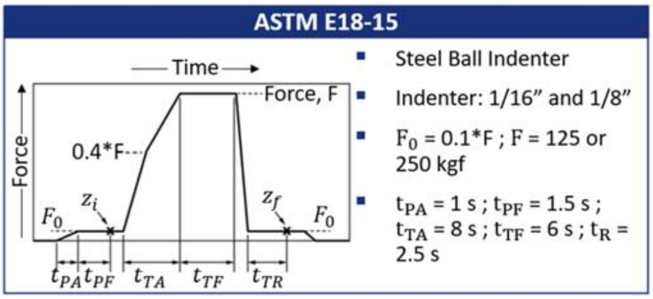

Fig. 2 Load Profile

The model's geometries were configured using a 3D deformable as the workpiece and a 3D discrete rigid spherical indenter, Fig. 3. To reduce the computational time, a ¼ symmetric body was used, constrained at the sides and bottom faces. The load was applied in two steps. The first steps consist in the loading profile shown in Fig. 2. In the second step the load was suppressed and a prescribed displacement in the opposite direction was applied, relieving the pressure and allowing the stresses on the body to stabilize.

To allow the workpiece penetration and the material flow through the indenter surface, the model was defined with the surface-to-surface contact method, configured with tangential and normal behavior. The sliding behavior was defined as a finite slide, due to its capability to follow the geometry of the master surface [3].

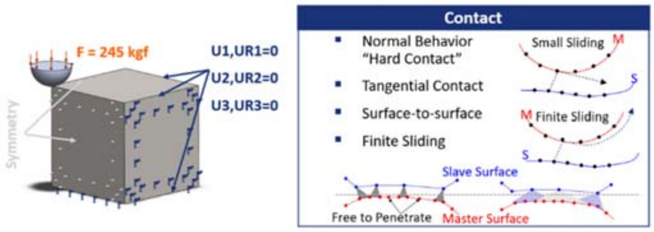

Fig. 3 Model configuration

The material applied to the workpiece was modeled with Johnson Cook's plasticity model, using the AISI4340 mechanical properties. For that, the elastic behavior was configured as an isotropic material with Young's Modulus = 205 GPa and Poisson's ratio = 0.3. The plasticity parameters of the Johnson-Cook model can be found in Table I.

TABLE I
MECHANICAL PROPERTIES AISI4340

A [MPa]	B [MPa]	C	n	m	$\dot{\varepsilon}_0$ $[s^{-1}]$	T_{Melt} [K]	T_{Room} [K]
635	402	0.055	0.26	1.03	0.294	1793	298

The workpiece on the indentation case was configured with 8-node linear brick elements with reduced integration and hourglass control (C3D8R), while the discrete rigid sphere was modeled with 4-nodes, bilinear quadrilateral elements (R3D4).

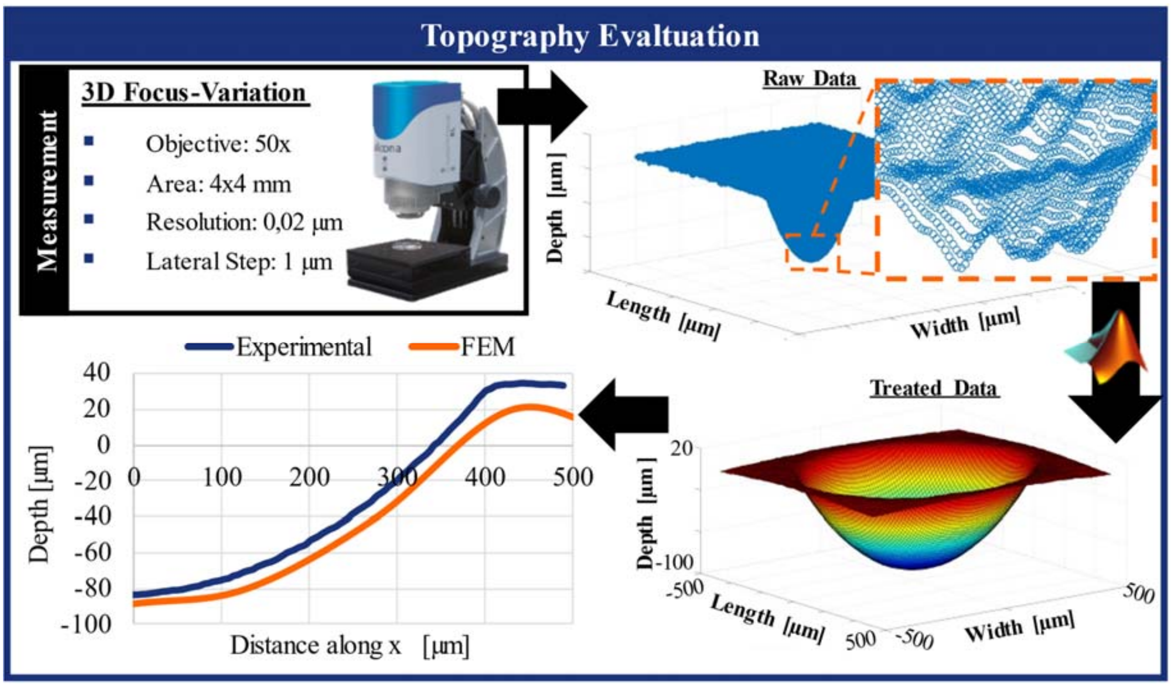

Fig. 4 Topography evaluation procedure

For the first experimental verification, the indentation profile was measured through a topography measurement performed by an Alicona Infinite Focus SL, a 3D Focus Variation microscope configured with an objective lens of $50\times$, that allows a resolution of 0.02 µm. The microscope provides a point cloud that was treated through MATLAB® to provide a surface mesh with the same size as the FE model. With the surface mesh, it was extracted a profile from the depth central point to the exterior of the indentation. This 2D profile was then compared to the depth obtained by the FE model. Fig. 4

summarizes the topography analysis method.

C. Grinding Model

The grinding model, representing the manufacturing process applied in this study, was built using the hybrid approach. This technique, used to predict the residual stress generated by a machining process, is shown in Fig. 5 [4]. With this approach, the contact between the tool and workpiece is substituted by its thermal and mechanical loads generated during the process.

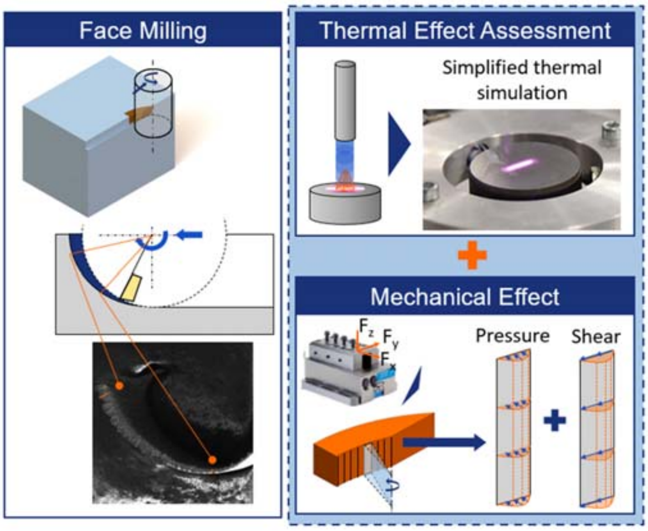

Fig. 5 Face milling simulation

As the grinding process is a machining process as milling, the same process used by [4] was applied. In his investigation, the mechanical loads were defined directly using measured data, from the experimental procedure made by Rego et al. [5]. The machining process was made in a 5-axis vertical CNC machining center Hermle C600 U with the three orthogonal forces measured by the piezoelectric platform Kistler 9625B. The induced residual stress was then experimentally measured on a PANalytical Empyrean stationary diffractometer using a $CrK\alpha1$ radiation with a vanadium filter.

Considering the virtual representative specimen used in the paper, shown in Fig. 6, the load distribution considers the three phases of grinding: the tool-workpiece contact beginning, full contact, and contact finishing, as presented in Fig. 6.

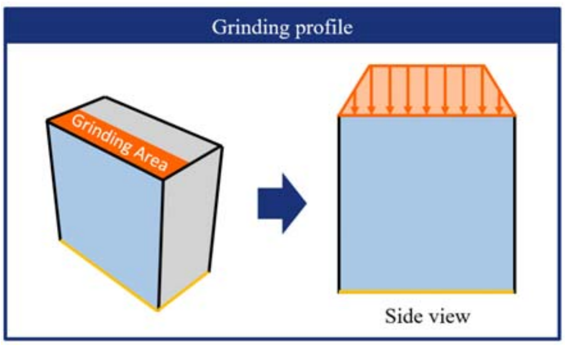

Fig. 6 Grinding Load

III. RESULTS

A. Indentation Evaluation

To evaluate the model, the indentation profiles obtained numerically were compared with experimental profiles obtained from four application cases configured with different indenter sizes and loads, Fig. 7. For each indentation case, 9 repetitions were made. The 9-points cloud obtained was then averaged and plotted as a surface, where a profile from the deepest point was extracted. It was observed that the combination of the smaller indenter, 1/16", with the highest load, 250 kgf, resulted in the deepest indentation. By contrast, the lowest penetration was achieved with the bigger indenter combined with a lower load. This can be explained by the pressure applied to the material that was then used to plastically deform the material, which will increase with the reduction of the indenter surface area.

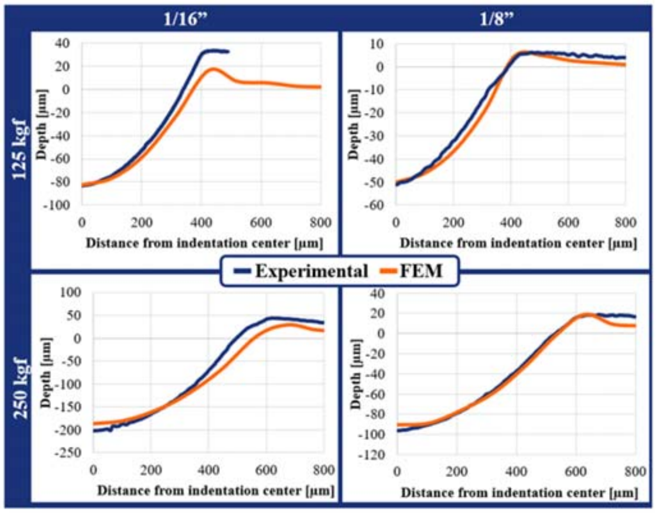

Fig. 7 Topography evaluation

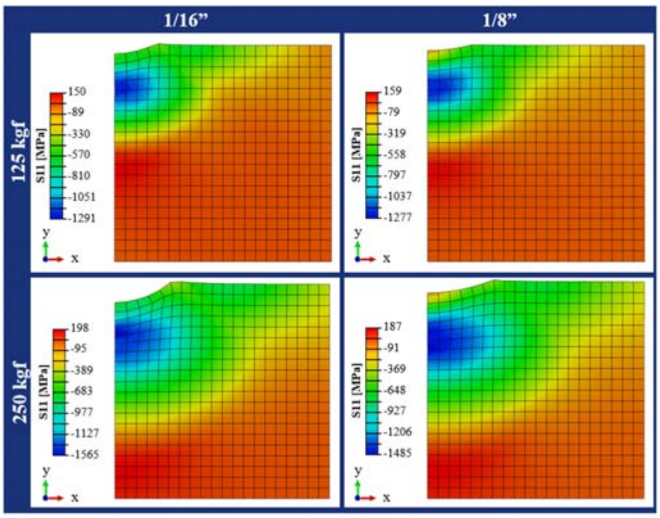

Fig. 8 Effect of increasing size and force

With the comparison between numerical and FEM results, an average deviation of 10% was observed. Therefore, it can be concluded that the contact algorithm and material model used in this study are representative of the material flow occurring when the indenter penetrates the workpiece. With the experimental verification, a comparison between the residual stress from each case was made to observe its relation with the increase of size and force, Fig. 8.

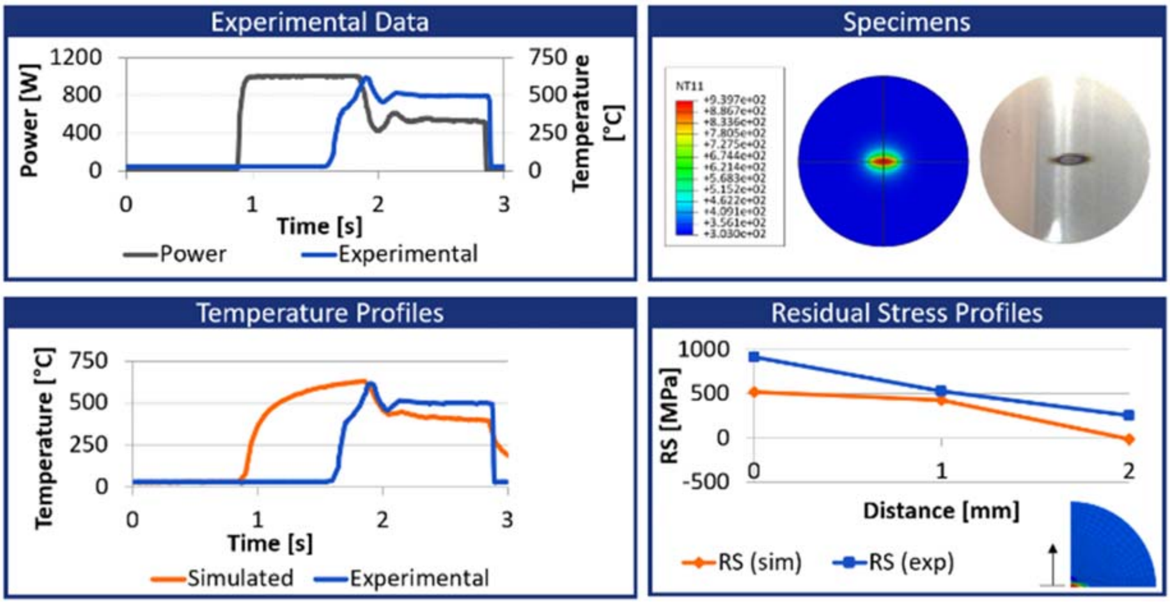

Fig. 9 Grinding model verification

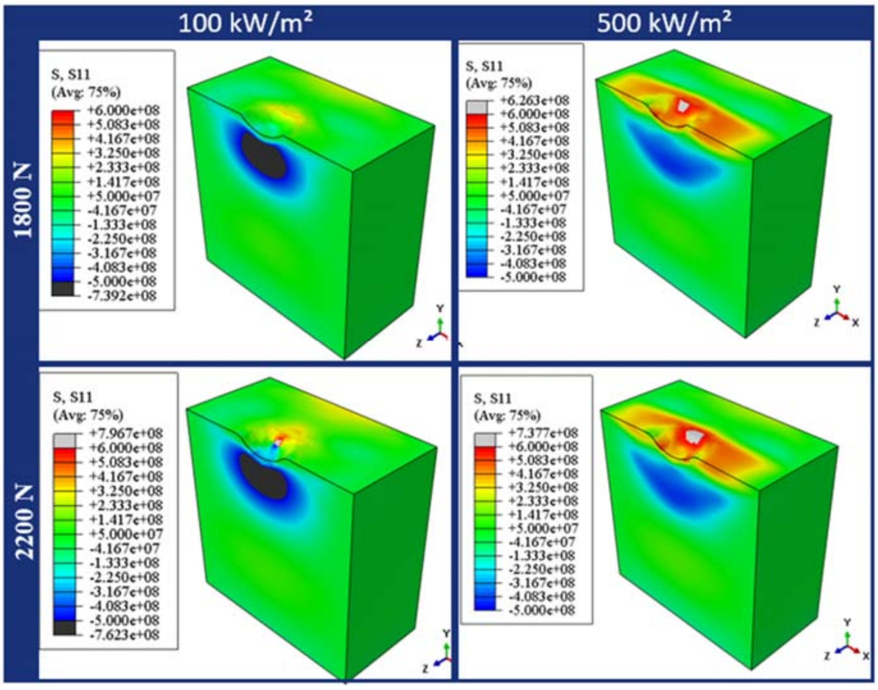

Fig. 10 Interaction effect on residual stress

Regarding residual stresses from each case, it can be observed that, when increasing the indenter force, not only the compressive area will increase, but also the value of the maximum compressive stress will increase. The increase of size will increase the distribution of the compressive stress but it does not significantly affect the values of the residual stress.

B. Grinding Evaluation

By comparing the numerical model results with the experimental it can be seen in Fig. 9 that both temperature profile and power are in good agreement. When analyzing the residual stress obtained from the thermal model a good agreement can also be seen between the experimental and numerical models. Therefore, the grinding model is coherent with the physical phenomenon.

C. Model Interaction

With both indentation and griding models representing the physical behavior of its experiments, the interaction between the numerical models can be investigated. The interaction was analyzed considering two indentation conditions, varying its loads from 1800 N to 2200 N with the grinding thermal load varying from 100 kW/m² to 500 kW/m². Fig. 10 presents the residual stress profile in the X-direction after the cooling step for these four combinations.

To analyze the grinding procedure effect on the indentation the residual stress along the depth was plotted for the case with the 2200 N indentation and 500 kW/m² grinding. It can be seen in Fig. 11 the modification caused by the grinding procedure on the indentation residual stress profile.

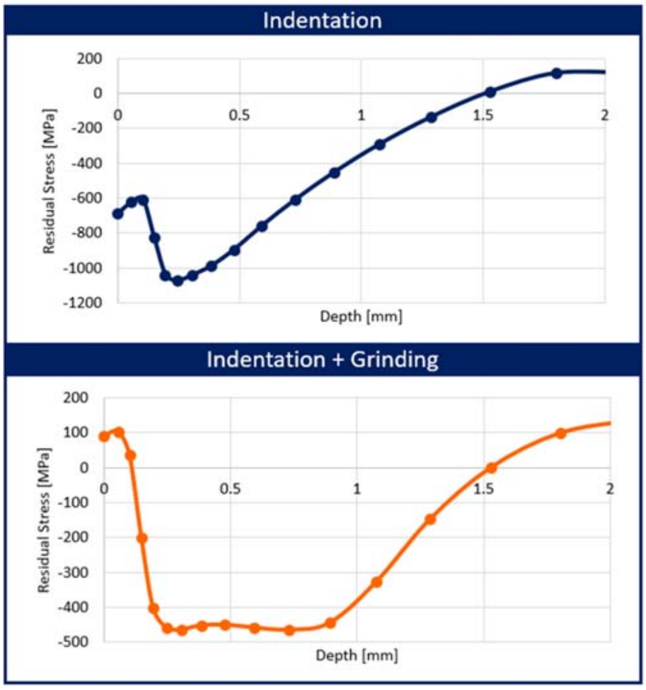

Fig. 11 Interaction effect on residual stress profile

IV. Conclusion

From the interaction results, it can be seen that the grinding will have a significant effect on the stress state of the indentation. It was observed that not only does the grinding procedure affect the compressive stress on the subsurface, but also generated a tractive region at the surface.

Overall, a substantial effect of the interaction on the stress state was observed. The results obtained must now be expanded and experimentally validated to be incorporated into manufacturing applications.

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