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RESIDUAL - STRESS AND TEMPERATURE FIELDS IN SURFACE TESTING: FINITE-ELEMENT ANALYSIS

Hasan Nazieh

Mechanical Engineering Department, Zarqa University, Zarqa, Jordan

Corresponding author: nazieh@ymail.com

Abstract. *Numerous advancements have been made to treat part surfacing, however, the presence of surface imperfections resulting from finishing processes has raised concerns about their potential to serve as stress concentrators. To address this concern, the present study utilized the power of the finite element method and cutting-edge software applications. The main aim of the study is to evaluate the stress-strain condition of material surfaces post-finishing, leveraging the comprehensive capabilities offered by these software systems. A significant component of the investigation centered on the influence of non-stationary temperature fields, as monitored by dynamic thermoelements, on the stress-strain dynamics within material surfaces. Visualization techniques were employed to depict the specified field functions, revealing notable variations in temperature distribution. The findings demonstrated that the standard function identified the highest temperature area within the 3-7-4 node segment, while the alternative function pinpointed it within the 4-node segment, indicated by the red area. These outcomes highlight the valuable role of non-stationary temperature fields in balancing the mechanical and physical aspects of the finishing process. This study contributes significant insights into the post-finishing stress-strain state of material surfaces, emphasizing the potential advantages of using modern software systems for in-depth exploration.*

Keywords*:* finite element method, information technology, serendipity finite element, stress-strain state.

1. Introduction

Surface quality plays a crucial role in determining the reliability and durability of equipment parts during operation. The roughness of air-engine blade surfaces, for instance, serves as a quality criterion for blade durability, fuel consumption, and engine efficiency [1]. A diamond stylus moving on an investigated surface is used to determine roughness parameters such as Ra and Rz [2]. Additionally, the quality of surface processing significantly influences the strength of parts [3]. For instance, imperfections formed during surface finishing are known to reduce significantly the fatigue strength of parts.

Various technologies are used for part surface treatment, including electric-powered diamond grinding, belt grinding, creep-feed grinding, polishing, electrochemical treatment, electrolytic plasma polishing, and ionic plasma hardening [4-6]. To eliminate the adverse influence of technological heredity, finishing treatment should be applied during the next processing operation to form compressive residual stresses in the surface layer. Uneven allowance removal leads to considerable instability in the residual stress indicator in surface layers. The process line for finishing material surfaces consists of units such as machine-tool fleet with numeric control (for example, grinding machine Metabo6NC-1000 [8] control equipment (measuring system BLAZER) [8], X-ray diffractometers X stress 3000 G3R [9], laser interferometers, robot manipulators with goniometers X stress Robot, etc.); and software systems for investigation of physical and mechanical components of surface processing. The use of ANSYS software is essential in investigating the physical and mechanical components of surface processing [1, 6]. In addition, Fused deposition modeling (FDM) is the most commonly adopted technique in additive manufacturing, as it is useful in the enhancement of the tensile strength of 0° raster specimens. According to Garg and Bhattacharya [10], Fused deposition modeling (FDM) is the most commonly adopted technique that is used in additive manufacturing techniques. Burley et al. [11] conducted an experimental study and addressed the impact of residual stresses in the near-surface region after the adoption of the plastometry technique. Liu and Guo [12] used a thermo–elastic–viscoplastic model using explicit finite element code to develop Abaqus.

The present study focuses on the profound impact of surface finishing on the fatigue strength of mechanical parts. In particular, the study observes the effectiveness of creep-feed grinding and polishing techniques in enhancing the fatigue strength of these components. This in-depth analysis emphasizes an examination of the microgeometry and microstructure of the upper boundary layers of the surface. The comprehensive insights gained from the study include revealing the complexities of the physical and mechanical properties of these components facilitated through the use of ANSYS software. This will help in identifying the optimal operational conditions for both the creep-feed grinding and polishing techniques. In parallel, it suggests that adopting these techniques could indeed lead to a significant enhancement in the fatigue strength of components.

The significance of this study lies in its unique contributions, particularly in shedding light on the transformative role of surface finishing, with specific emphasis on creep-feed grinding and polishing techniques, in strengthening component fatigue strength. Through these findings, the study enriches the understanding of the surface finishing process and its far-reaching implications on the mechanical attributes of components. Beyond this, the study has evolved to offer practical recommendations, aimed at refining the surface finishing process to enhance the longevity and reliability of equipment components during their operational lifecycle.

2. Related Work

The finite element method is a mathematical technique used to analyze and investigate the stress-strain state and field functions of materials based on the theory of elasticity. It is widely used in engineering and material science research to model and simulate the behavior of complex structures and systems. One important aspect of the finite element method is the use of finite element approximations, which are mathematical models used to estimate the behavior of a system. One such approximation is the serendipity finite element, which is a type of quadrilateral element with nodes at the corners and in the middle of each side. The serendipity finite element was originally developed to simplify the calculation process by reducing the number of internal nodes required for accurate modeling. However, the standard functions of serendipity finite elements have been criticized for their unnatural nodal load distribution, which can result in inaccurate calculations.

The apparatus of the finite element method [12-13], is used to analyze and investigate the stress-strain state and field functions based on the theory of elasticity. The mathematical support of the finite element method serves as an algorithmic basis for the following software systems: Nastran, Ansys, Solid Works, etc. Lagrangian finite elements have nodes in the middle of the final element. Internal nodes increase the calculation scope and are not used for assembling finite elements. There are unidentified disadvantages in serendipity finite elements. The initial goal of creating serendipity finite elements is the ability to convert an arbitrary quadrilateral into a square and to reduce the calculation scope by removing extra internal nodes. This curvilinear element appeared in the calculation of structures as a serendipity finite element.

The higher the order of the serendipity finite element, the more accurate the calculation is. A square finite element combines well with a triangular simplex, forming an effective mesh of the finite element method. The square cells are convenient within the area, and triangular–in the boundary area during digitization of a planar area in arbitrary configuration. The basic function plays a key role in the finite element method; therefore, its physically adequate form is important. A serendipity finite element interpolates the element boundary function and approximates the nodes inside it. The main drawback of standard functions of the serendipity finite elements is unnatural nodal load distribution from a single mass force because loads are negative in corner nodes [13]. These standard functions [14] play a double role in isoperimetric technology. In Zienkiewicz's [14], standard model, there are no additional degrees of freedom (df), because it is designed according to hard recipes of matrix algebra within the La-grange interpolation formula [15].

The first alternative (physically adequate) model of serendipity finite elements appeared in 1982 due to the inability to find a rational explanation for unnaturally distributed uniform mass force [14]. Serendipity finite elements with negative loads at nodes are not suitable for computer testing. Doudkin et al. [16] presented a three-dimensional solid-state model based on computation. This study also analyzed feed elements of rods of vibroscreen. According to the results, the strengths of materials varied but their parameters did not report a change for the bulk materials. A study by Shukla, Murmu, and Deo [17] used Finite Element Method software for modeling the fracture behavior of plain concrete (PC) and basalt fiber concrete beams for Mode I (Three-point bending). The findings outlined that the results of the finite element simulation were favorable and no effect was reported in the fracture energy along with the varying sizes of specimens. Campaner [18] reported that despite restorative material, the tensile stress magnitude of the region of the prosthetic connectors was the highest. However, none of the modern software systems (finite element method oriented) contains alternative functions of the serendipity finite elements. Results of the constructive theory of serendipity approximations are laid down (as algorithmic functions) in two information technologies [19], developed based on Turbo Pascal and C#, respectively, and in the automated subsystem, developed based on Delphi.

2.1 Research Gap

The finite element method is a mathematical technique used to analyze and investigate the stress-strain state and field functions of materials based on the theory of elasticity. It is widely used in engineering and material science research to model and simulate the behavior of complex structures and systems. One important aspect of the finite element method is the use of finite element approximations, which are mathematical models used to estimate the behavior of a system. One such approximation is the serendipity finite element, which is a type of quadrilateral element with nodes at the corners and in the middle of each side. The serendipity finite element was originally developed to simplify the calculation process by reducing the number of internal nodes required for accurate modeling. However, the standard functions of serendipity finite elements have been criticized for their unnatural nodal load distribution, which can result in inaccurate calculations.

3. Materials and Methods

3.1 Field Functions for Residual Stress Prediction

The field functions $U(x, y, t)$ is used for conducting visualization and analysis tests of surfaces or non-stationary physical tests, which include temperature field and stress field. These field functions are custom-tailored to the requirements of residual stress prediction and represent a fundamental component of the present study. Equation 1 summarizes the field functions needed:

$$U(x, y, t) = \sum_{i=1}^{m} N_i * f_i(t) \tag{1}$$

Where: Ni is the standard or alternative basis of the serendipity finite element, t is time, I is node number, m is the number of nodes of the serendipity finite element, fi(t) is the law of time variation of a physical quantity (residual stress, temperature, etc.) at the boundary nodes of the serendipity finite element.

The field functions defined by Equation 1 are employed to visualize and analyze non-stationary temperature fields and stress fields. In particular, they are utilized for the prediction of residual stress in materials. Through the application of these field functions, the residual stress fields within the material samples are visualized and analyzed. The functions are integral to this process, and their unique design allows for the precise identification of regions with residual compressive stress, residual tensile stress, thermo-elastic stress, and residual stress in our specimens. The field functions are systematically adapted to the preferred physical quantities in the surface control points. This facilitates the investigation of residual stress in materials and ensures their direct relevance to our study objectives.

The applicability of these field functions is not confined to material surfaces with linear boundaries. Through the incorporation of isoperimetric transformation techniques, they can effectively handle surfaces with curvilinear boundaries, thus extending their utility. The surface area with a curvilinear boundary does not matter, due to the isoperimetric transformation. The standard and alternative function fields are presented in the following equations. The standard function [19].

$$N_i = \frac{1}{4}(1 + x_i x)(1 + y_i y), x_i, y_i = \pm 1, 1, 4$$

$$N_i = \frac{1}{4}(1 + x_i x)(1 + y_i y)(x_1 x + y_i y - 1), x_i, y_i = \pm 1, 1, 4$$
$$N_i = \frac{1}{2}(1 - x^2)(1 + y_i y), y_i = \pm 1, i = 5, 7$$
$$N_i = \frac{1}{2}(1 - y^2)(1 + x_i x), x_i = \pm 1, i = 6,8$$

The alternative function:

$$N_i = \frac{1}{4}(1 + x_i x)(1 + y_i y) x_i y_i x y, x_i, y_i = \pm 1, i = \overline{1, 4}$$
$$N_i = \frac{1}{4}(1 - x^2)(1 + y_1 y)^2, y_i = \pm 1, i = 5, 7$$
$$N_i = \frac{1}{4}(1 - y^2)(1 + x_1 x)^2, x_i = \pm 1, i = 6, 8$$

3.2 Sensitivity Analysis and Optimization

To address the effects of various input parameters on the simulation results and to identify critical parameters that require control or optimization, the methods incorporate a sensitivity analysis. Furthermore, optimization techniques are seamlessly integrated to determine optimal design parameters and processing conditions that lead to the desired stress-strain state within the material surfaces.

A two-dimensional finite model was adopted in the study, and the length of the edge was 20 times larger than that of the uncut layer to ensure steady-state cutting. The type of element used was a four-node bilinear, but not all elements in the mesh were placed longer in the horizontal direction to account for intense compression and shear straining for the movement of the tool from right to left. This shape was selected to reduce the likelihood of numerical problems that may be encountered due to the distortion of elements.

The detailed algorithm with considerations for temperature fields, stress fields, sensitivity analysis, and optimization techniques has been provided in Appendix A.

3.3 Validation of Method for Residual Stress Prediction

Tests were conducted on material samples with known residual stress profiles. Residual stress was measured directly using established techniques. The measurements were then compared to the predictions generated by the method, calculating performance metrics such as MAE and RMSE. When experimental validation is not feasible, benchmark data with known residual stress profiles is used. The method was applied to predict residual stress within the same materials and geometries used in the benchmark data. Performance was evaluated through metrics and visual comparisons. The method's response to variations in input parameters was assessed, evaluating its robustness and reliability. The results of both experimental and numerical validation validated its applicability in scientific studies and practical applications.

4. Results and discussion

The square area of the processed surface area based on serendipity finite element of the first and second order is presented in Fig. 1 and 2. For a square of the first order (Fig. 1), a visualization and analysis test has been conducted using the MATLAB software package for a stationary field of residual stress. The values of residual stress ($\sigma_{residua}$l) in four control nodes were determined by X-ray diffractometer stress 3000 G3R (second node of the process line) based on the electric-powered diamond grinding. The required range of computed values of residual stresses are:

$$\sigma_{1residual} = 25MPa, \sigma_{2residual} = 34MPa, \sigma_{3residual} = 42MPa, \sigma_{4residual} = 37MPa$$

The two-dimensional surface of the test stationary field of residual stress is shown in Fig. 3. The field has a clear gradient, and permanent relief (due to zero curvature), the highest concentration of residual stress is concentrated at the third node (purple area), and the lowest in the first (green area). In the element barycenter, the value of the residual stress is σcenter=residual = 34.5 MPa (arithmetic mean), which is confirmed by a uniform gradient. There are no anomalous areas (vortices) on the field surface. Recommendations for subsequent finishing are identified from the removal of stresses in the third node area.

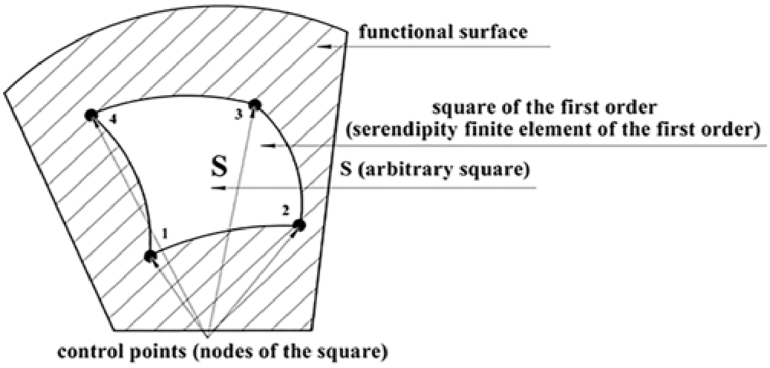

Fig.1. Square of the first order.

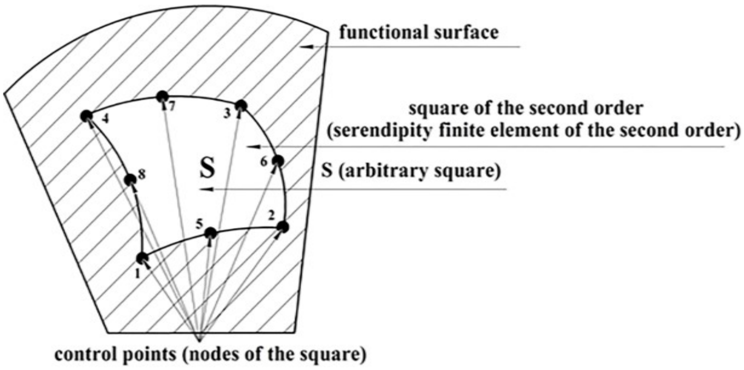

Fig.2. Some functions of the Square of the second order.

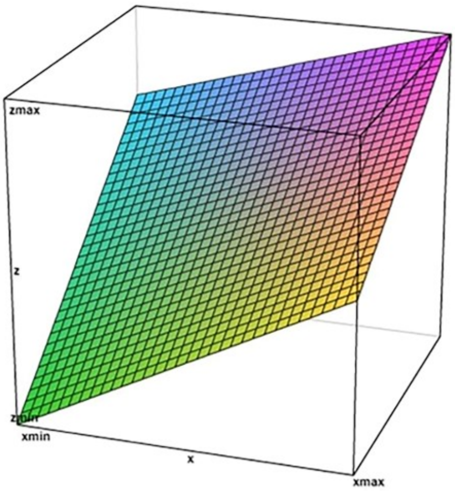

Fig.3. Testing in MATLAB.

A visualization and analysis test has been conducted for a stationary temperature field using dynamic thermos-elements for a square of the second order. Equation 3 presents the following function:

$$U(x,y) = \sum_{i=1}^{8} N_I * T_i$$

The temperature values in eight control nodes were determined with a contact thermocouple (the second node of the process line) because of the belt grinding (temperature perturbations at the points of changed trajectory of the tool moving). The desired range of values: T1=120°C, T2=134°C, T3=147°C, T4=151°C, T5=125°C, T6=139°C, T7=148°C, T8=118°C. Fig. 4 shows the two-dimensional surface of the tested stationary field using the standard function. The field has a smooth gradient, and saddle-shaped relief (hyperbolic paraboloid). The highest temperature area is concentrated in the 3-7-4 node segment, whereas the lowest temperature area was shown in the 5-node segment transitioned into the barycentre (blue area). There are no irregular regions on the field surface. Therefore, operations should be processed by reducing the high-temperature area in the 3-7-4 node segment. Fig. 5 shows the two-dimensional surface of the tested stationary field using an alternative function.

The field has a clear, transient gradient, and wave-like relief (Jacobi function). The highest temperature area is concentrated in the 4-node segment (red area), whereas the lowest temperature area was in the 2-node segment (blue area). There are vortexes (localization in the center) on the field surface. Therefore, process steps should be undertaken by reducing the high-temperature area in the 4-node segment.

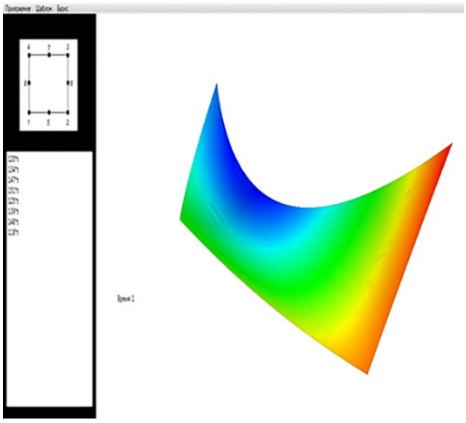

Fig.4. Standard Function

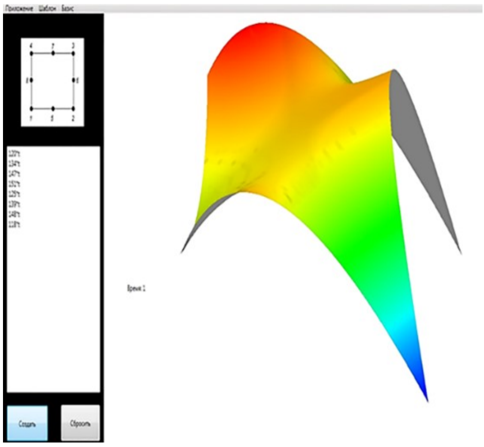

Fig.5. Alternative Function.

For the stationary field of residual stress, a square of the first order was used, and a visualization and analysis test were conducted using MATLAB software. The results showed that the highest concentration of residual stress was concentrated at the third node, and the lowest in the first. The value of the residual stress at the element barycenter was determined to be 34.5 MPa, which is confirmed by a uniform gradient. There were no anomalous areas on the field surface, and recommendations for subsequent finishing were identified from the removal of stresses in the third node area.

For the stationary temperature field, a square of the second order was used, and two-dimensional surfaces of the tested stationary field using the standard and alternative functions were analyzed. The results showed that the highest temperature area was concentrated in the 3-7-4 node segment for the standard function and in the 4-node segment for the alternative function. The lowest temperature area was shown in the 5-node segment transitioned into the barycenter for the standard function and in the 2-node segment for the alternative function. There were no irregular regions on the field surface for the standard function, but vortexes were present in the center for the alternative function.

Based on these results, the study made recommendations for subsequent finishing operations to reduce the high-temperature or residual stress areas in the identified node segments. However, it's worth noting that the results presented in the study are limited by the specific conditions and materials used in the testing. The study did not compare the results with other methods or models, and the conclusions drawn are only applicable to the specific conditions tested.

5. Conclusions

The study has used non-stationary temperature fields with dynamic thermoelements. Two different function fields were undertaken to establish an application of analysis and visualization of the physical and mechanical components of the finishing process. Through the application of simulation models and modern software systems such as MATLAB, the study successfully determined residual stress and temperature values in various control nodes, offering valuable insights into the effects of finishing on material surfaces. These findings hold significant implications for the field of material finishing, highlighting the potential for enhancing the quality and performance of finished materials. While this study provides valuable insights into the stress and temperature patterns of material surfaces during finishing, there is still much to be learned and explored in this field. By continuing to innovate and refine our approaches to analysis and visualization, we can continue to improve the quality and performance of finished materials, and advance the field of material science as a whole. The findings of this study have important implications for the field of material finishing. The use of non-stationary temperature fields with dynamic thermoelements, in combination with the finite element method and modern software systems such as MATLAB, has demonstrated the potential for analysis and visualization of the physical and mechanical components of the finishing process. By using simulation models, the study was able to determine the values of residual stress and temperature in various control nodes, providing insights into the effects of finishing on material surfaces.

Conflict of interest statement

The author declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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AUTHORS' INFORMATION

Hasan, Nazieh – PhD, Assistant Professor, Mechanical Engineering Department, Zarqa University, Zarqa, Jordan; SCOPUS Author ID: 57201666796; ORCID iD: 0000-0001-8017-5633; nazieh@ymail.com