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Steelpan Sinking Quality Approach Employing Dynamic Nonlinear Finite Element Method

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Abstract

Steelpan (or pan) is recognized as Trinidad and Tobago's national musical instrument. The flat portion of a steel drum is deformed during the sinking process, producing the bowl for the playing surface. This paper presents a three-pronged methodology that aims to improve this sinking process. The approach comprised the development of procedures identifying sheet deformation properties; examination of dynamic loads carried by hammers onto both surface strain and dimple depth; and describing the optimum hammer criteria. This methodology encompasses the development of procedures and tools to identify and simulate sheet metal strains and hammer dynamics. Sheet metal testing standards were employed in conjunction with a custom-built jig and fixture to measure surface strains. The creation of a finite element analysis (FEA) modeling dynamic interactions between hammer and sheet was facilitated by a COMSOL Multiphysics simulation. The paper provided sample results for both simulated and experimental tests. A sensitivity analysis was recommended to reduce strain offset errors using the Taguchi method. This preliminary work to develop a methodology laid the groundwork for evaluating hammer geometry. It encourages exploration with diverse materials and impact settings, understanding of the dynamic interplay for improving the quality of the sinking process in the pan industry.

Keywords
Steelpan, Deformation, Strain, COMSOL and Hammer

1. Introduction
This section provides a contextual foundation for the research, outlining the rational, aims and objectives for setting the stage to provoke a revolution to promote the need for an official work standard to manufacture the pan. The standard is envisioned to be a cornerstone for preserving the rich cultural heritage embedded in the efforts of the historical events leading to continue the great successes of the pan industry.

1.1 Background
The pan, recognized as Trinidad and Tobago's national musical instrument, maintains cultural significance, and has sustained the attention of a global audience. The pan industry manufacturing practises comprise a series of adjustable steps that depend on the choice of equipment and techniques passed on from the specialists. The pan has customarily been produced with newly fabricated mild steel drums but in most cases the industry would use recycled drums.

The six major steps to build the instrument (Maloney 2011) involved:

1. ***Sinking***: Stretching of the drum with a hammer to create the sink profile.
2. ***Shaping note regions***: The notes are formed into sections of individual humps.
3. ***Grooving***: Punch marks are formed around along note boundaries.
4. ***Cutting the drum***: The skirt is formed when the rest of the drum is separated leaving the pan. The side of the drum is not cut for the bass pan.
5. ***Firing***: The paint or oil on the surface is removed by heating and there is possibly some strain relief for the deformed areas in preparation for further cold working during tuning.
6. ***Tuning***: The note fundamental and harmonics are introduced and refined in the note by peening the note area.

The deformation process in Step 1, Sinking (also known as dishing or drop hammer forming) involves the shaping of the flat portion of the drum into the sink. Figure 1 illustrates a typical layout of the notes following the curvature of the sink on the playing surface (Kronman 1991).

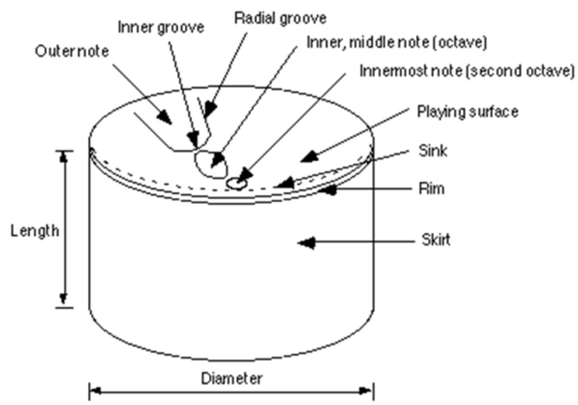

Figure 1. Layout of a typical pan.

The shotput, modified sledgehammer, and enhanced pneumatic ram were the main drop hammer forming tools (Figure 2) that were developed and still used in the pan industry to sink the drum to form the playing surface. The low capital cost of the hammer tools and small production rates of the industry has overshadowed the implementation of other experimentally accepted processes like spinforming and marforming (Lewis et al. 2005). The hammer forming tools are controlled in a sequence to create a series of incremental dimples on the flat surface to create the sink.

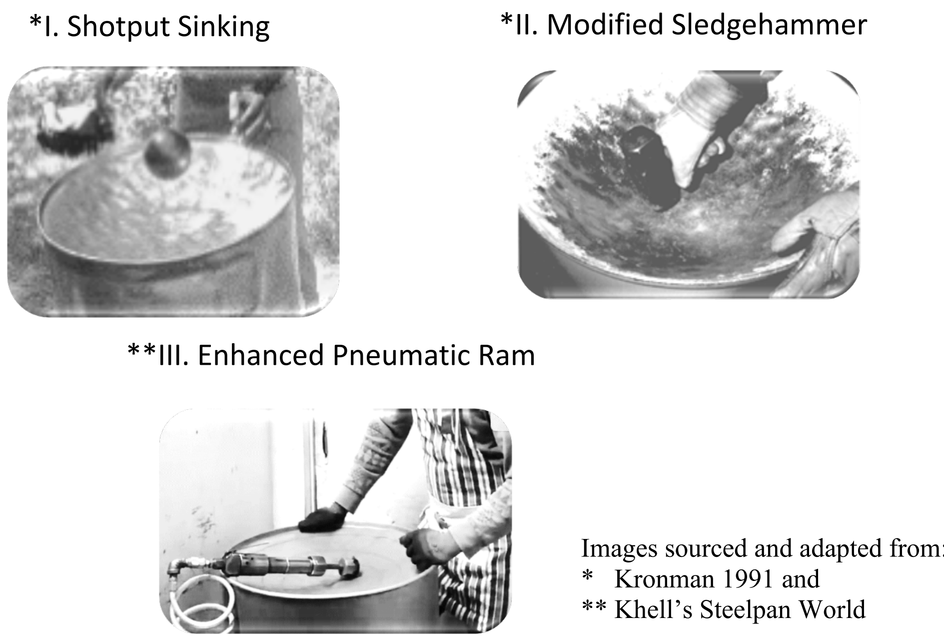

Figure 2. Incremental hammer forming tools for sinking pan.

Notwithstanding the significance of the other steps to convert the drum into a pan, it should be acknowledged that this sinking procedure alters the geometrical, mechanical, and metallurgical features of the material to be further formed into notes. Recognizing the effects of the hammer provides opportunities to enhance both the working standard for the pan and the quality of the instrument itself. This paper's primary goal has been to outline a methodology for optimizing sinking in pan manufacturing as part of a continual improvement scheme in the pan industry.

1.2 Significance of the Study

The bowl produced from sinking the sheet faces the greatest accumulation of plastic strain (permanent deformation). Furthermore, the accumulated work with the hammer can be labor-intensive over long periods with a potential to develop the personal injury vibration white finger (VWF). The need for a shift to reduce the sinking time resulted the replacement of the manual method (hammer driven by hand) with a semi-mechanized method (pneumatic powered ram, Figure 2). The significance of this study lies in its potential to reform pan manufacturing through the development of the three-pronged methodology proposed in this research. This methodology supports the industry by providing a foundation for quality, including advancements concerning safety and efficiency for the pan industry. Quality can be achieved through industry standards providing the framework to a continued legacy for this national instrument. Finally, it sustains a cultural identity and a global appreciation of the unique musical tradition surrounding the pan.

1.3 Aim and Objectives

This research aims at creating a standardized method to predict surface strains on the dimple developed after a single hammer impact. The objectives for the development of this methodology include: 1) Identify mechanical properties for sheet deformation, 2) Build a jig and fixture to produce one dimple from a hammer for the collection of empirical data on the hammer and sheet, 3) Develop a FEA (Finite Element Analysis) simulating the mechanics of the build in objective 2, and 4) Demonstrate the deployment of the simulation.

2. Literature Review

This chapter presents the historic evolution of pan manufacture describing the origins and stages of substantial developments to sink the drum. It then examines earlier techniques for sinking process optimization, shedding light on the methods adopted in the past to form the bowl profile of the pan. This review also addresses the positive and negative effects observed in pan production, setting a way for the methodology proposed in this study.

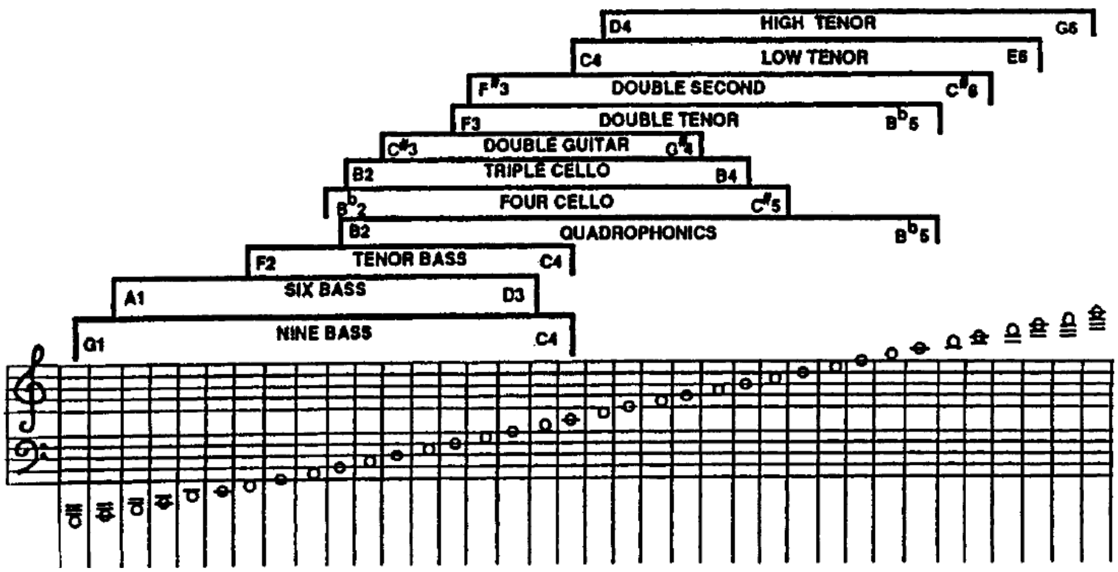

Figure 3 Common Note Range of Each Pan Instrument.

2.1 Historical Evolution of Pan Manufacturing

The pan is regarded as the most recognized musical instrument developed in the 20th century (Rossing et al. 1996). Since then, its popularity has been growing in the international market. The development of the pan occurred between 1935 -1945 during the reign of the tamboo bamboo musical bands. These bands would comprise instruments made of almost any material that percussively complemented the band's motive. The quest to be the best sounding rhythmic band spurred musicians to a mode of experimentation on their own instruments. By accident, musicians realized that metal containers produced different pitches when stretched by hammering. This eventually led to the first pan known as the ping pong, which was constructed with sufficient notes to perform a melody (NCCTT 2020). Since then, the instrument has been and not limited to ranges from the bass, $\mathbf{G}_1$ to the soprano, $\mathbf{F}_6$ (Achong 1996). The results of a survey presented in Figure 3, demonstrates an extension of Achong's range and showing where the musical voices overlapped each other on the musical scale (Pichary 1990).

2.2 Previous Approaches to Sinking Process Optimization

Regrettably, drums used for the pan were of low-grade steels and material specifications were vague and unreliable (Gay 2000). Successful cases observed show that many depend on the label to determine which drum was suitable to produce a pan. Another method involved knocking the flat side of the drum and listening for a preferred response with the trained ear. Although many use these techniques, a more precise test may involve determination of the thickness, chemical composition, and mechanical properties of the drum material. The lack of consistent quality drums and primitive methods for testing the material contributes to the difficulty and debate in the industry for an official standard. The pan industry recognizes and has called for the standardization of the drum material supplied (Marshall 1985). In response, researchers have identified methods and provided results of several characteristics that contributed to a good pan. There were hardness tests that showed an inverse relationship between the thickness distribution and surface hardness after the pan was crafted (Murr et al. 1999). After observing the drums being sunk by multiple practitioners, they all followed the same sequence described by (Kronman 1991), to achieve the hardness surface profile. Step 1 in Figure 4, shows where the sequential pattern for guiding the hammer initiates from the outer section going in a circle about the center. After every concentric round, the dimple formation continued inwards toward the center. This was followed by step 2 where the hammer was guided in a swirling pattern. Steps 1 and 2 were repeated sometimes interchangeably to progressively maintain an axisymmetric bowl as the depth of the sink profile increased.

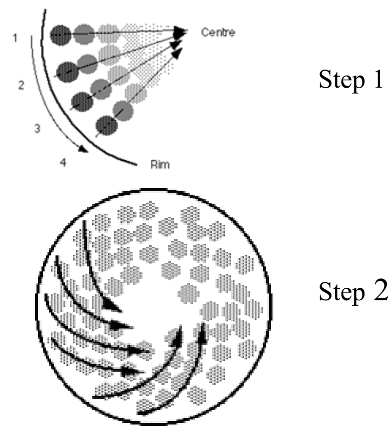

Figure 4. Sinking hammer sequence.

This hammering pattern was able to produce a reducing thickness profile toward the center of the bowl which eventually gives rise to the continuous work hardening results on the surface. Further studies on the material behavior showed the acoustic relationship between the developed strains (thinning of sheet thickness) and hardness during sinking (Murr et al. 2006; Tello 2000).

In this case the unknown quality of steel drums used for pans pose the pan manufacturer an issue of maintaining a consistent product and the engineering solution for correcting the personalized processes of each manufacturer to develop a consistent pan. This dilemma of an inconsistent supply of non-recurring quality drums impedes the steps to standardization of pans necessitating a thorough examination of the manufacturing process and an exploration of potential enhancements to ensure product reliability. The inconsistent supply of drums, coupled with recurring quality inconsistencies, pose a significant threat in pan manufacturing, especially for the mass production of the instrument. However, the unpredictable nature of steel behavior during the sinking process becomes a formidable obstacle when the base material properties remain unknown. The substantial demands of being part of the idiophone family place the pan at risk of not meeting predefined properties. This emphasizes the critical need for a comprehensive understanding and control of the mechanics of sinking to ensure consistent quality in pan production. A meticulous adjustment to process parameters activates a process for sinking optimization. This includes the precise control of deformation variables during the sinking process. Tuning of the model corrects the parameters providing a decent prediction of the deformation cycle, minimizing irregularities for quality enhancement of activities involving instrument and industry. Figure 5, presents the thickness differences between an initially sunken drum and a sunken drum fully patterned, heat-treated, and partially tuned. This indicated no reduction in the area near the rim; about 50% reduction toward the bottom and the grooved areas around the notes revealed an additional 10 – 15% reduction (Murr et al. 1999).

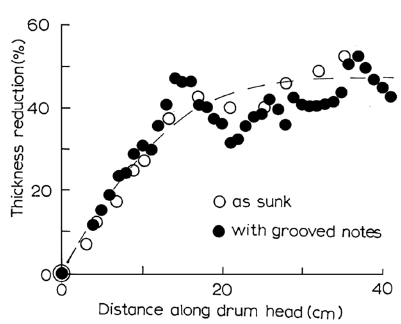

Figure 5. Thickness reduction in drum cross-section.

2.3 Challenges in Sinking Techniques

This section will be a synopsis of the challenges including details mentioned previously. The materials of drums used were not specifically designed for the pan. As a result of the non-standardization of drum material, an unpredictable material deformation response would require high levels of skill and intuition. From an engineering perspective, the combination of a low grade and unknown material composition provided a perceived low level of confidence in the quality of the instrument.

It has been observed that the pan industry experimented with hammer materials including hard woods, sledgehammers of varied diameters and almost any metal objects close to a hemispherical profile. As previously mentioned, the semi-mechanized approach to sink the pan has replaced the manual method shortening the sinking time.

As the industry continues to use different types of hammers, the accumulated strains in the final pan product may have variations producing an inconsistent pan. Final deformed shapes may vary by the significant impact on the spring-back forces produced during deformation. Additionally, decreasing the hammer diameter resulted in a lower deviation error in the produced sheet (Asgari et al. 2015). The preceding literature in this study justifies the need to specify the strains on the sheet for the pan to aid in the determination of the most suitable version of the hammer for the process.

3. Methods

This section describes the tools and procedures within the scope chosen to systematically collect and analyze data for the study. During this description, sample solutions of the simulation were also provided to enhance comprehension and applicability of the approach employed to discover the influences of hammer diameter on surface strains. The method additionally considers the dynamic loads and contact between the hammer and sheet during deformation. This consists of model development, verification, and validation procedures using empirical data on parameters involving sheet deformation. It also employs standard mechanical tests complemented by the creation of a custom jig and fixture. The process to develop the three-pronged methodology comprised a thorough review of literature on the process to sink a pan, drop hammer forming and FEA employing COMSOL Multiphysics.

This methodology guides the study's execution, ensuring the collection of reliable and meaningful data for the strain model and experiment. Specification of experimental material includes details such as thickness, material composition, and any other relevant characteristics that might impact the deformation behavior. Furthermore, the dynamic variable specifications include hammer velocity and other factors influencing the deformation process. The data collection methods, and instrumentation were determined to achieve the objectives defined to guide the methodology's formulation. A simplified scaled down physical model was developed and built to test the hammers of varying diameters. The scaled version would not represent the accumulation of strains developed by the repeated formation of dimples in the sequence shown in Figure 4 for the pan. It would be simplified to an axisymmetric model (Kwiatkowski et al. 2010) with a blank receiving one blow of a hammer. The empirical data from the physical model will be further used for the validation of the FEA simulation. A design of experiments was chosen to observe surface strains and dimple depth for hammers of varying diameters factoring the sizes used in the industry; a controlled velocity to produce a dimple depth accepted in the industry; and a material proven for the pan that was readily available. The method used to measure strains in the scribed grid method was employed for both physical experiments and FEA simulation. In other words, the linear displacements across similar points on the surfaces were accessed ignoring the curvature of the deformed blank. The former statement was a special consideration given to the constraints and limitations reducing the study to predict the linear displacements (between two points) physically measured in the scribed grid method.

4. Design Methodology for FEA Model

The methodology should explicitly acknowledge the historical variations in sinking tools, emphasizing the context within which the study was conducted. The models were designed to be like the Enrichsen test (Reddy et al. 2013; Talapatra et al. 2013; Meric et al.1997). Figure 6 shown below, illustrates the experiment set-up and representation of the two-dimensional axisymmetric model of the hammer and blank arrangement. The model environment was designed for examining strain distribution. The precision and accuracy of replicating the physical experiment was directly limited to the parameter processing in COMSOL Multiphysics Software. Specification of shapes, size, and spatial connections was crucial to the success of the model. The study took the form of a simplified scaled-down physical model of the drop hammer process. The design comprised a fixture that concentrically clamps a blank between plates. The jig guides a free-falling interchangeable hammer toward the center of the blank for impact.

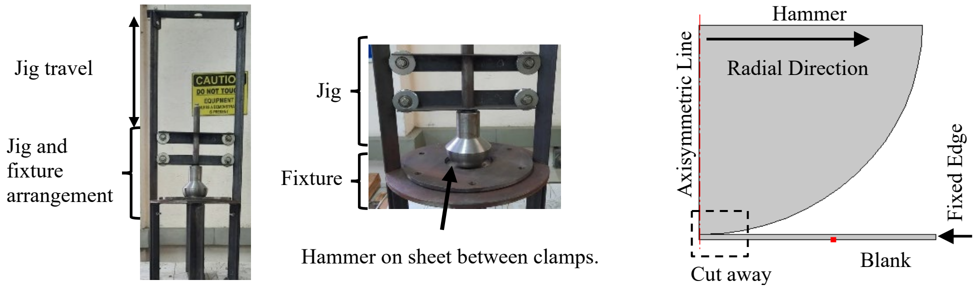

Figure 6. Experiment set-up and finite element model.

4.1 Constitutive Equations

From the onset, as the hammer contacts the material, elastic deformation conditions were initiated following relations in Equation 1 for motion until yielding occurs.

$$\frac{E}{2(1+\nu)}\left(\nabla^2\mathbf{u} + \frac{1}{(1-2\nu)}\,\nabla(\nabla.\mathbf{u})\right) + \mathbf{f} = \rho\frac{\partial^2\mathbf{u}}{\partial t^2}$$

Equation 1 Motion during sheet deformation of a linear elastic material.

Where E = Young's modulus, ν = Poisson's ratio, **u** = Displacement vector, ρ = Mass density, and **f** = Force per unit volume.

After the sheet yields, a plastic deformation regime was introduced creating an elastoplastic system (Ibrahimbegovic 2009). Then Ludwik-Holloman power law equation was adopted in the model for the nonlinear relations of stresses and strains (Ghosh 2006).

$$\sigma_1 = \sigma_0 + K(\varepsilon_{\text{pe}})^n$$

Equation 2 Ludwik-Holloman power law.

Where σ_1 = Final stress, σ_0 = Initial stress, K = Strength coefficient, ε_{pe} = Equivalent plastic strain, and n = Strain hardening exponent.

For this time-dependent studies, the exponential dynamic coulomb friction model, Equation 3 can be considered once all the parameters were available.

$$\mu = \mu_{\text{dyn}} + (\mu_{\text{stat}} - \mu_{\text{dyn}})exp^{-\propto_{\text{dcf}}\|\text{V}_{\text{slip}}\|}$$

Equation 3 Dynamic coulomb friction.

$$\mu = \mu_{\text{stat}}$$

Equation 4 Static coulomb friction.

Where μ = Friction Coefficient , μ_{dyn} = Dynamic friction coefficient, μ_{stat} = Static friction coefficient, $\propto_{\text{dcf}}$ = Friction decay coefficient, and V_{slip} = Slip velocity

The updated friction forces are estimated and do not account for changes influenced by the environmental conditions (Hol et al. 2012). Alternatively, V_{slip} of Equation 3 would tend to zero quickly for the short duration of impact. Considering that the hammer was in contact for a short period and V_{slip} decelerates to rest, the exponential expression quickly reduces to one and the μ_{dyn} expression cancels, leaving the static friction coefficient as shown in Equation 4.

4.2 Material Parameters

To accurately simulate strains, material properties must be specified to closely represent responses of the experiment material used for this study. The material for both hammer and blank was modeled as SAE1008 mild steel.

Additionally, the following physical variables were specified for the model before deformation: Blank Thickness = 1.2 mm, Blank Diameter = 106 mm, Hammer Mass = 6.458 kg, and Hammer Diameter = 60, 80, and 100 mm.

4.3 Material Mechanical Properties

The physical experiment involved a series of tests to determine the sheet metal mechanical properties for the model in this study. The chosen material was submitted to controlled instances that cause deformation reactions retrieving material qualities loaded under tensile conditions. This focused testing attempts to determine how the materials respond to stresses, giving critical data for further strain analysis during the sinking hammer optimization process for pan manufacture. Material properties $E = 180$ GN/m^2, $\sigma_y = 188$ MN/m^2, $K = 513$ MN/m^2, and $n = 0.207$ were determined according to ASTM E8 and ASTM E646 testing standards. A friction coefficient, $\mu = 0.5$ was assumed for this model case.

4.4 Mesh Type and Size

The triangular meshing arrangement was key to ensuring an accurate displacement solution for the contact between the hammer and blank (Wang and Budiansky 1978; Aljibori and Hamouda 2009).

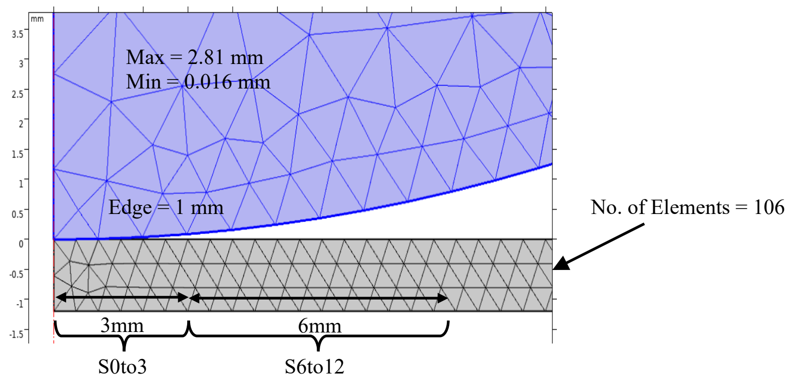

Figure 7. Meshing of model (Cut away from Figure 6).

Figure **7** shows a cut away of the model to compare the distribution and sizes of elements chosen. The modeled hammer starts with a fine mesh size between 2.81 and 0.016 mm at the core and edges with a constant element length of 1 mm. The element size chosen for the blank (the material studied) was half the size for the hammer edge.

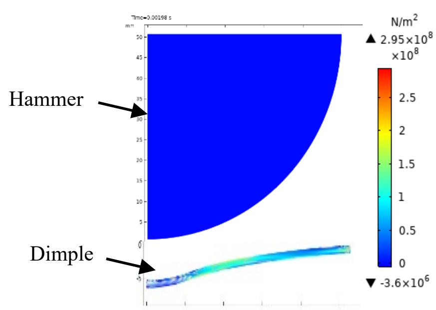

Figure 8**.** FEA stresses solution

This was achieved by specifying the number of elements in the part. Figure 8 illustrates a sample solution for the hammer of diameter 100 mm. The residual stresses distributed through the material can be observed along with the geometry of the dimple after the period of hammer contact.

4.5 Methodological Approach

This research explored the dynamic interplay between hammer features and sheet steel behavior throughout the sinking process. The study used a combined technique of FEA Simulation and Physical Experiment to understand complexity of the nonlinear dynamics behind surface strain, dimple depth, and sinking tool optimization. The methodology focused on the cohesive mixing of virtual and empirical areas, giving important insights for refining the science of pan fabrication. Figure 9 demonstrate the activities involved in the methodology for this study.

The FEA Simulation appeared to be a robust virtual tool for deciphering the intricacies of the sinking process in the field of pan manufacture. The simulation journey begins with the construction of a model environment that replicates the pan formation's actual circumstances with the careful creation of geometric items that include the sheet metal blank and sinking hammer experiment. The precision of material variables and parameters directly affects the solutions of the simulated sheet metal for the applied boundary conditions in the process.

Boundary requirements defined by physics ensure that the simulation captures the limitations and interactions between the studied components. The process of creating a mesh simplifies intricate geometry into smaller, more manageable components, improving the simulation's numerical accuracy. The computation of surface strain and dimple depth, which was the simulation's ultimate result, provided primary data on the behavioral patterns of nonlinear strain during sheet deformation.
Simultaneously, the physical experiment starts the investigation of the pan sinking procedure. The environmental mechanics were well described, encapsulating the atmospheric and spatial circumstances that are essential to the experiment. Determining the design limitations becomes crucial to establish the parameters to follow the physics of the experiment. With an emphasis on controlled impact experiments, a physical apparatus that mimics the single impact of a hammer on mild steel sheet was created as the real experiment took form.

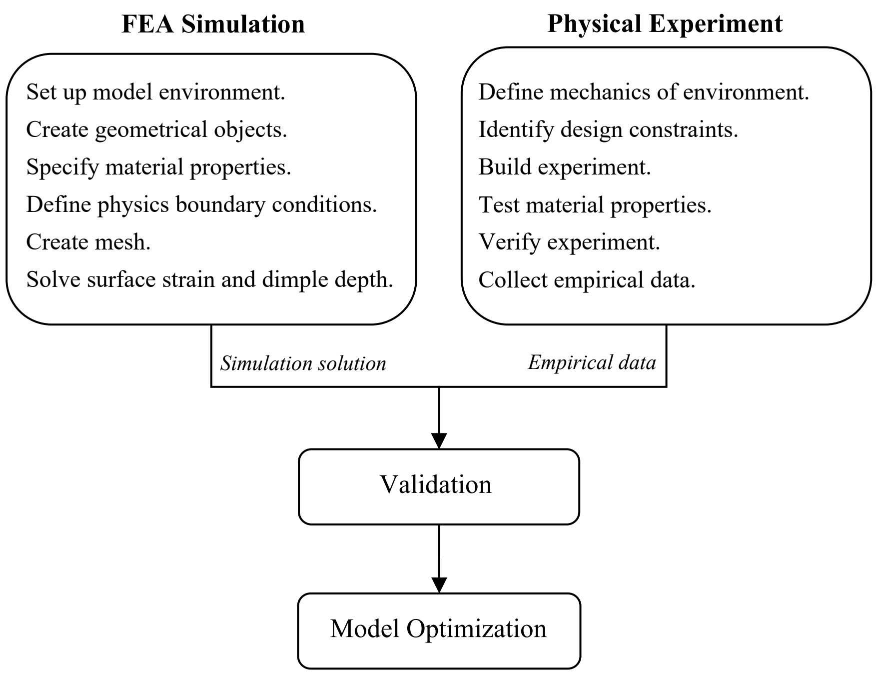

Figure 9. Diagram of methodological approach.

Empirical trials are used to examine material qualities and reveal the subtleties of mechanical behavior. Verifying the experiment guarantees that the setup was in accord with the desired design for the gathering of empirical data. The convergence of the physical experiment and FEA simulation marks a juncture, guiding the validation process (Tekkaya and Martins 2009). By leveraging empirical data from the real experiment, the simulation's results are rigorously validated, creating a robust benchmark. A meticulous examination of integers and coherencies fosters effective communication between the virtual and physical domains, fortifying the reliability of the study's findings. This validation step stands as a crucial benchmark, ensuring that the simulated model faithfully replicates the dynamic subtleties observed in the actual experiment. The strength of the study's results lies in the validation's ability to establish agreement between the simulation and actual data, thereby enhancing the validity and applicability of the study's findings. In the case the validation tests fail, the Taguchi method usually accompanied with an Analysis of Variance (Zareh et al. 2013), would be the methodical approach to perform the sensitivity analysis, to correct and optimize the simulation's settings (Mitra 2011; Karna and Sahai 2012; Freddi et al. 2019).

5. Results and Discussion

For the case demonstrated in this paper, Figure 10 illustrates the velocity profile representing a pneumatic piston to model the mechanics of the hammer. COMSOL Multiphysics software facilitated the simulation of the finite element model employed to analyze the dynamic interaction between hammer characteristics and sheet steel behavior.

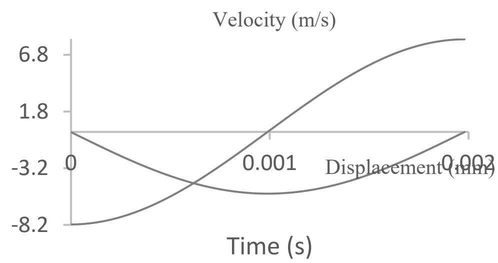

Figure 10. Hammer mechanics

The graphical representation in Figure 11 illustrates consistent simulated displacements at the center of the dimple across various hammer sizes.

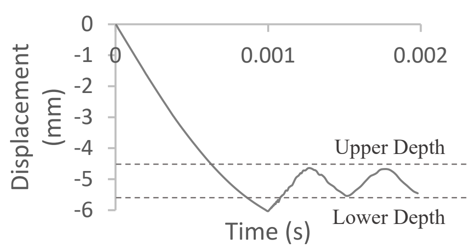

Figure 11. Range for maximum sheet displacement

At 0.001 seconds after the reversal of the hammer direction, the material exhibited an oscillating pattern, a phenomenon visually captured in the radial strains depicted in Figure 12. Notably, these oscillations were prevalent

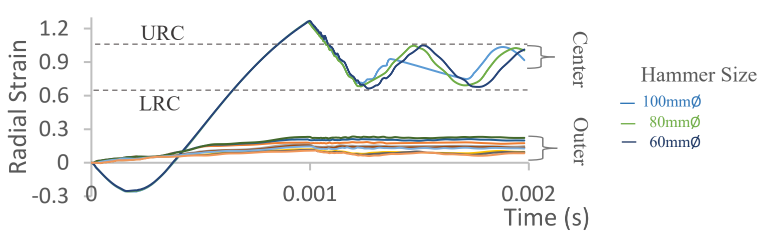

Figure 12. Strain behavior on sheet

at the centers for all hammer diameters. Progressing towards the fixed ends of the blank, there was a discernible decrease in the magnitudes of strain. Additionally, the simulation revealed a noteworthy trend of increasing compressive strain towards the center of the blank during impact, particularly up to 0.0004 seconds. This nuanced analysis provides valuable insights into the dynamic behavior of sheet metal, contributing to a deeper understanding of the pan manufacturing process. The model's depth results (Figure 11) were near the experiment's which would also be consistent for sinking pans. On the other hand, before model tuning, experimental strain results (Figure 12) were not within the range between the models upper and lower values. Similar patterns revealed increasing strains near hammer contact surfaces at the center of the blank, decreasing towards the sheet's fixed ends. A sensitivity analysis was proposed to improve systematic errors with the Taguchi method.

This pattern was prominent in instances of larger contact diameters, potentially attributed to the frictional forces generated during the hammer's descent onto the blank. The concluding oscillation cycle depicted in the graph of Figure 12 indicated that the strain recovery occurred in phases, mirroring the descending order of hammer diameters. Hammers with diameters of 60 mm and 80 mm exhibited a similar trend, with the 80 mm strain reactions being marginally quicker. The strain reaction at a 100 mm diameter was comparable but erratic (at 0.0014 - 0.0017 s), possibly influenced by additional friction arising from the larger contact surface area. The application of a concentric impulse load by this hammer model with a hemispherical profile affirmed significantly lower strains in the outer region of the blank. This observation implies a concentration of strain activities primarily around the contact surface between the hammer and the blank, while the remaining portion of the blank demonstrated an ability for elastic recovery. This highlights the nuanced distribution of mechanical forces in this specific scenario, revealing a dynamic relationship between strain concentration and elastic recovery that enhances our comprehension of the material's response to such impact loading conditions.

5.1 Model Validation

The following illustrates an attempt to validate the model strain and depth parameters with the experimental results. As previously discussed, the parameters were oscillatory in nature. The choice of validation required that the experimental strain and depth measurements fall within the upper and lower range extracted from the model solutions.

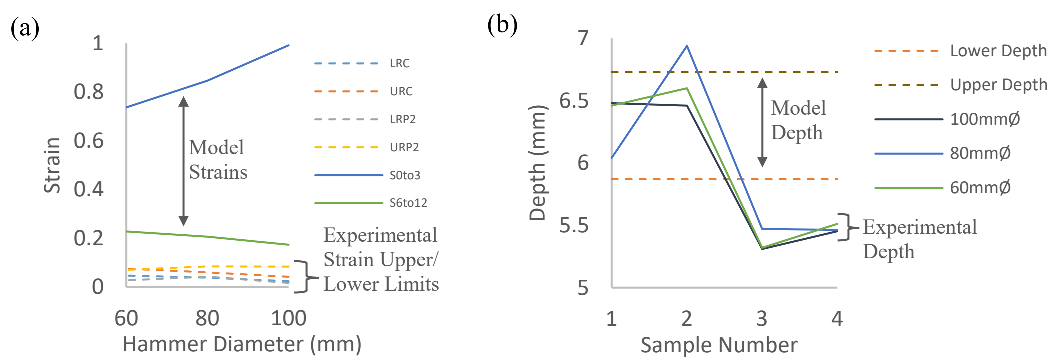

Figure 13. Validation of model strain and depth results.

The graph in Figure 13(a) compares measured experimental strains for positions S0to3 and S6to12 (refer to Figure 7) with upper and lower model strains for the three hammer diameters. The upper (URC) and lower (LRC) limits were determined from the peaks and valleys on the graph in Figure 12. From the onset, experimental strains do not fall within the model limits indicating that the model be tuned to ensure the solutions are valid. Subsequently, referring to Figure 13(b), the model's upper and lower depths were determined like the strains (refer to Figure 11) and depths were measured from experiment samples for each hammer diameter. At present, the pan industry accepts a dimple depth of approximately 6mm and there are no strict acceptable depth tolerances after impact. The experiment depths highest and lowest value registered were 6.94 mm and 5.32 mm, respectively, which was near the model depth. It would be anticipated that a sensitivity test would improve the model by identifying which variable increases the variance for the solutions. This procedure would attempt to reduce the error between the empirical and model responses.

5.2 Long Term Impact Study

The methodology for optimizing the drop hammer process was proposed to transform changes in the pan industry with intentions to enhance quality and production efficiency. With a thorough grasp of sheet deformation properties and dynamic hammer interactions, manufacturers stand to benefit from the implementation of more robust quality control measures with respect to a hammer design. Moreover, an additional step to the pathway to foster innovation using modern computational tools has been revealed, safeguarding the instrument's cultural heritage while expanding its appeal to new markets. The establishment of a standardized practice has the potential to bolster the industry's credibility, supporting innovative growth opportunities and a sustainable manufacturing practice in the long term.

5.3 Economic Analysis
Potential savings for the pan industry may result from improved production efficiency, reduced waste, and an enhanced product. A qualitative analysis of the economics to adopt the proposed methodology shows a potential for cost savings at the initial investment and operational stages. It also allows manufacturers to identify areas for optimization and cost reduction, thereby maximizing the return on investment and assuring product reliability. For example, initial investment costs may include expenses in the procedure to approve a new hammer design. Rather than performing physical tests, a simulation alternative lowers research and development costs without compromising the lead time to introduce a new hammer to the manufacturing line. Additionally, the methodology promotes industry innovations through the exploration of improved hammer and raw materials for the instrument with potential for reduced sheet failures, faster production time, safety advancements and an acoustically consistent musical product.

5.4 Proposed Improvements
Additional adjustments to the parameters, meshing schemes, and material representations in the simulation will be carried out based on the knowledge gathered after the validation stage. To better align the virtual representation with the intricate dynamics seen in the real experiment, this effort would strive to use the iterative nature of the optimization process. Despite the present restriction of employing just one type of material, future studies aim to establish the strain behaviors for different hammer and sheet material alternatives with the hope of adapting new materials to the industry.

6. Conclusions
This research intricately navigated the dynamic nuances inherent in the pan formation process, unraveling the complex interplay of excitation forces, mass, stiffness, and displacement reactions, embracing both elastic and plastic deformations. This methodology attempts to integrate the insights from the pan's formation into a comprehensive dynamic framework modeling nonlinear strain behavioral patterns for the evaluation of sinking tools.

Through meticulous simulations, a discernible relationship emerges between the displacement and strain of the blank, revealing insights into the dynamic characteristics of the pan manufacturing process. The focus on dimple depth and strains provides an understanding that serves as the root of the study's contribution to the standardization of the pan. The core of the methodology involves a meticulous examination of the impact of varying hammer diameters on the performance of a steel sheet. This investigation yields valuable information crucial for the design and optimization of sinking hammers, with a specific aim to achieve desired strain regimes essential in pan sinking. The controlled impact forces, coupled with the variations in hammer diameters, generate a dataset for selecting the most suitable hammer diameter, offering practical and applicable insights for the pan industry. The methodology as a guide for the pan industry should foster a culture for precision and efficiency in crafting pans. The intention through the lens of this methodology was to encourage the advancement and continued application of science and engineering in pan.

To enhance the hammer's performance in terms of diameter, strategic opportunities for improvement can be explored. Firstly, a thorough evaluation of the hammer's design, especially for larger contact diameters, becomes critical. This entails refining the shape and composition to mitigate erratic strain reactions observed at a 100 mm diameter. Adjustments to the profile or surface modifications may help minimize frictional forces during the hammer's descent onto the blank. Secondly, optimizing impact dynamics would be essential for achieving a smoother and more predictable strain response. Fine-tuning weight distribution, surface finish, or impact angles could ensure a more uniform strain distribution across the sheet. Lastly, insights from the sensitivity analysis using the Taguchi method together with the Analysis of Variance Method can inform targeted enhancements in the hammer design, considering factors affecting the variables that significantly influence strain behavior. By systematically adjusting parameters based on these insights, the goal would be to achieve a more consistent and efficient sinking process.

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