A TECHNICAL ANALYSIS AND DESIGN OPTIMIZATION STUDY OF A MINI-TRACTOR POWER TAKE-OFF (PTO) SHAFT FOR SMALL-SCALE AGRICULTURAL APPLICATIONS

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ABSTRACT

Efficient power transmission to agricultural machinery has become increasingly important for enhancing the productivity and operational capability of modern farming systems. Power take-off (PTO) mechanisms play a central role in this regard by enabling the direct transfer of engine power from a tractor or prime mover to a wide range of external implements. Although PTO systems have long been integrated into high-horsepower tractors and automotive machinery, such equipment often remains financially inaccessible for small and marginal farmers, particularly those operating on limited landholdings. This challenge underscores the need for an optimized and cost-effective PTO transmission system that can meet the diverse requirements of small-scale agricultural operations.

This review examines the functional characteristics, performance capabilities, and technical advantages of PTO systems in contemporary agricultural practices. The study highlights the PTO's ability to efficiently transmit mechanical power to a variety of essential farm implements, including rotavators, generators, water pumps, and other auxiliary devices. By facilitating the use of multiple attachments with a single power source, PTO mechanisms enhance operational flexibility, reduce machinery redundancy, and support sustainable farming practices. The findings reaffirm that PTO technology remains a highly effective and reliable method for power transmission within agriculture. Its adaptability, mechanical efficiency, and compatibility with a broad range of implements make it indispensable for meeting the evolving needs of farming communities, especially those seeking affordable and versatile mechanization solutions. The review emphasizes the continued relevance of PTO systems and the need for further innovation to improve their accessibility and performance for small-scale farmers.

Keywords: *Gear, PTO Shaft, Power Take-Off, Mini-Tractor Mechanization, FEA, EN8, 20MnCr5 and ANSYS*

Introduction

The Role of Mini-Tractors in Small-Scale Farming

The agricultural landscape in many regions, particularly in India, is dominated by small-scale and marginal farmers. Statistical data indicates that over 80% of India's cultivators fall into this category, with an average of 72% owning less than 5 acres of land[1]. For these farmers, traditional methods such as bullock-driven plows present significant challenges, including high operational costs, substantial maintenance, and low returns. In parallel, conventional, high-horsepower tractors are often unaffordable, difficult to maneuver in small fields or orchards, and uneconomical for their needs due to high purchase and maintenance costs[1], [2], [3]. This economic and operational gap necessitates the development of compact, efficient, and affordable agricultural machinery, such as mini-tractors, that are specifically tailored to the unique requirements of small landholdings and diversified farming practices[4], [5], [6].

The primary objectives established for this dissertation work are multifaceted. First, to assess the technical feasibility and commercial advantages of incorporating a PTO into a mini-tractor, a function not typically found in this class of machinery[7]. Second, to execute the detailed design of the PTO drive, including the gears and shaft, for a specified speed and torque[1], [8], [9]. Third, to perform a two-pronged stress analysis on the proposed design:

an analytical calculation of gear contact stress using Hertz's equation and shaft shear stress, followed by a comparative analysis using the Finite Element Analysis (FEA) software ANSYS 15[10]. This dual-method approach is intended to validate the theoretical calculations. Finally, the study aims to compare the performance of two distinct materials, EN8 and 20MnCr5, to determine the optimal choice for this high-demand application[11], [12]. The engineering choices made in this analysis—from the selection of material to the precise calculation of stresses—are a direct response to the market's need for a durable and low-maintenance product that can reliably perform tasks in challenging conditions, such as tilling tough, stocky grasses or working in wet, muddy soil[13], [14]. The successful execution of this design will ultimately determine if the customer's demand for a truly effective PTO-equipped mini-tractor is met in the long term[15], [16].

Foundational Principles of PTO Shaft and Gear Design

Overview of Gear Stress Mechanisms: Bending and Contact Stresses

The longevity and performance of any gear system are intrinsically linked to its ability to withstand operational stresses. Gears are typically subjected to two principal types of stress: bending stress and contact stress[17], [18]. Bending stress occurs at the root of the gear teeth, acting as a cantilever beam[18], [19]. This stress can lead to tooth breakage, particularly under repeated cyclic loading, a phenomenon known as fatigue failure[20]. Contact stress, on the other hand, is the pressure generated where the surfaces of two meshing gear teeth meet[20]. High contact stress can cause pitting or spalling on the tooth surface, which compromises the gear's structural integrity and can lead to premature wear and failure[21]. The original review study correctly identifies the analysis of gear bending stress as a key area for future investigation, acknowledging its critical role in the overall design and durability of the PTO system[22], [23].

Figure 1. Model Prepared in Creo+.

Theoretical Models for Stress Calculation

Several classical analytical models have been developed to calculate these stresses. For bending stress, the Lewis equation is a foundational method that models a gear tooth as a cantilever beam with a bending load distributed across its face width[8], [18]h. The formula incorporates a Lewis Form Factor (Y) to account for the gear's geometry and a velocity factor, often derived from the Barth equation, to factor in the effects of dynamic loading. For contact stress, the classical Hertzian contact stress analysis provides a framework for evaluating the deformation of smooth elastic bodies pressed together. While these models are invaluable for initial design estimations, they are based on simplifying assumptions. For instance, the Lewis model neglects stress concentration and assumes a uniform load distribution and that only a single pair of teeth is in contact at any given time. Similarly, the Hertzian analysis assumes frictionless contact between idealized cylinders[24], [25]. These simplifications highlight the need for more advanced validation methods to accurately represent the complex, real-world stresses a PTO system experiences.

The Role of Finite Element Analysis (FEA) in Design Validation

Finite Element Analysis (FEA) is a powerful numerical technique used to predict a component's behavior under real-world conditions by discretizing the geometry into a mesh of smaller, simpler elements. FEA software, such as Ansys Mechanical, provides a dynamic and integrated platform to simulate a wide range of physical phenomena, including structural stress, vibration, and heat transfer[26], [27]. Unlike the simplifying assumptions of classical methods, FEA can accurately model complex geometries, account for stress concentrations, and simulate dynamic and nonlinear loading conditions.
The initial study performed a comparative analysis between analytical calculations and FEA results for the PTO shaft's shear stress[28], [29]. The findings from this comparison are particularly telling. The analytical calculation for EN8 steel produced a shear stress of 17.189 MPa, which was in very close agreement with the ANSYS result of 17.17 MPa, a negligible difference of approximately 0.11%. This strong correlation confirms that for this specific loading condition, the simplified analytical model is a reliable predictor for EN8. However, a more notable discrepancy was observed with 20MnCr5 steel. The analytical result of 17.17 MPa was approximately 4.35% lower than the ANSYS result of 17.917 MPa. This difference, while still within the realm of "good agreement," underscores the value of FEA. The higher stress value from the FEA model likely reflects its ability to capture subtle geometric features, such as stress concentrations at keyways or splines, that are not considered in the basic analytical shear stress equation. As such, the FEA result for 20MnCr5 should be regarded as a more accurate and conservative value for safety and design considerations, validating the use of FEA as an essential tool for nuanced and realistic analysis.

Material Selection and Property Analysis

The choice of material for the PTO shaft and its gears is a critical determinant of the system's performance, durability, and cost-effectiveness[10], [30]. The initial study compared two materials, EN8 and 20MnCr5, based on their mechanical properties and found 20MnCr5 to be the superior choice. A deeper analysis reveals the fundamental metallurgical reasons behind this conclusion.

Properties and Suitability of EN8 Steel

EN8 is a medium-high carbon steel with a carbon content typically ranging from 0.40% to 0.45%. It is widely recognized for its favorable balance of mechanical properties, including good tensile and impact strength, and excellent machinability. As a cost-effective alternative to mild steel, EN8 is a common choice for general engineering components that require more strength and durability than can be achieved with low-carbon steels. Its typical applications include axles, shafts, and crankshafts. While EN8 can be heat-treated to improve its hardness and strength, it is not optimized for the deep case-hardening processes that are essential for components subjected to high wear and surface-contact stresses.

Properties and Suitability of 20MnCr5 Steel

In contrast, 20MnCr5 is a low-alloyed case-hardening steel. Its chemical composition, which includes manganese (1.25%) and chromium (1.15%), is specifically designed to enhance its hardenability. This material boasts significantly higher mechanical properties than EN8, with a tensile ultimate strength of 1000 MPa and a yield stress of 680 MPa, compared to EN8's 650 MPa and 465 MPa, respectively. These higher values translate directly to a greater load-bearing capacity and resilience under stress. Furthermore, 20MnCr5 is specifically used in the manufacturing of high-stress and high-wear components such as gears, shafts, and transmission parts, where a combination of surface hardness and core toughness is paramount.

The Strategic Advantage of Case-Hardened Steels in Driveline Components

The fundamental advantage of 20MnCr5 over EN8 is not solely its higher mechanical strength but its suitability for case-hardening. The process of carburizing diffuses carbon into the surface of the steel, creating an extremely hard outer "case" while maintaining a tough and ductile core. This unique microstructure is precisely what a PTO shaft and its gears require. The hard surface provides excellent resistance to wear and surface fatigue from constant friction and contact, which are major failure modes in driveline components. Simultaneously, the tough core prevents brittle failure from impact loads or sudden shock, ensuring the component's structural integrity and long-term reliability.

While EN8 can be flame or induction hardened for improved surface hardness, it cannot achieve the same level of wear resistance and fatigue strength as a properly carburized 20MnCr5 component. This difference in manufacturing potential is the critical factor that makes 20MnCr5 the superior choice. The superior material properties and the ability to enhance its performance through heat treatment mean that a 20MnCr5 component will have a greater endurance limit, leading to a significantly longer service life in the field. This directly aligns with the economic needs of the target market by reducing the frequency of maintenance and replacement costs. The following table provides a comprehensive comparison of the two materials, highlighting the key distinctions that influenced the final material selection.

Table 1. Mechanical Properties and Chemical Composition.

Mechanical Properties	**EN8**	**20MnCr5**
Tensile Ultimate	650 MPa	1000 MPa
Yield Stress	465 MPa	680 MPa
Young's Modulus	2e5 MPa	2.1e5 MPa
Poisson Ratio	0.3	0.3
Density	7870 kg/m^3	7850 kg/m^3
Chemical Composition (%)		
Carbon (C)	0.40–0.45	0.20
Manganese (Mn)	0.70–0.90	1.25
Silicon (Si)	0.05–0.35	0.25
Phosphorus (P)	0.06 max	-
Sulfur (S)	0.06 max	>0.035
Chromium (Cr)	-	1.15

Table 2. Manufacturing & Applications.

Case Hardening	Limited effectiveness	Excellent (Carburizing)
Wear Resistance	Moderate	Excellent
Machinability	Excellent	Good
Typical Use	General engineering components, axles	High-stress gears, shafts, transmission parts
Cost Relative to Mild Steel	Cost-effective	Higher (Low-Alloy Steel)

METHODOLOGY AND SIMULATION VALIDATION

Analytical Stress Calculation: Principles and Application

The analytical phase of the study involved calculating the shear stress on the PTO shaft. For a solid circular shaft subjected to a torsional load, the maximum shear stress (τ_{max}) is calculated using the torsion formula:

$$\tau_{max} = \frac{T \cdot r}{J}$$

where T is the applied torque, r is the shaft's radius, and J is the polar moment of inertia. This fundamental engineering principle provides a straightforward method for a first-pass stress estimation. The initial study used this approach for the shaft shear stress and also employed Hertz's equation for gear contact stress, establishing a theoretical baseline for the design. These calculations provide quick, yet simplified, estimations based on idealized geometry and loading conditions.

Finite Element Modelling and Meshing in ANSYS

To validate these theoretical calculations and account for real-world complexities, a Finite Element Analysis (FEA) was performed using ANSYS 15. The geometric model of the PTO system was first prepared in CREO software.

Figure 2. Stress analysis of EN8.

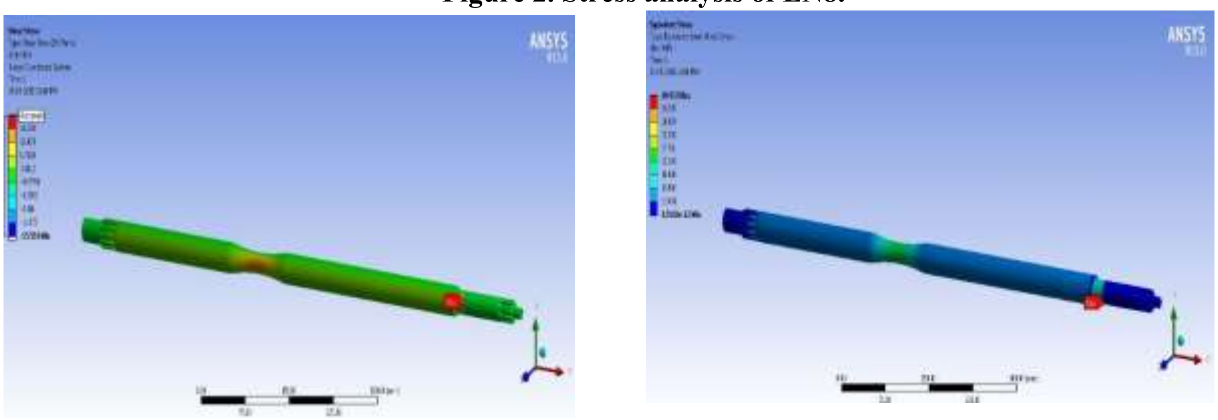
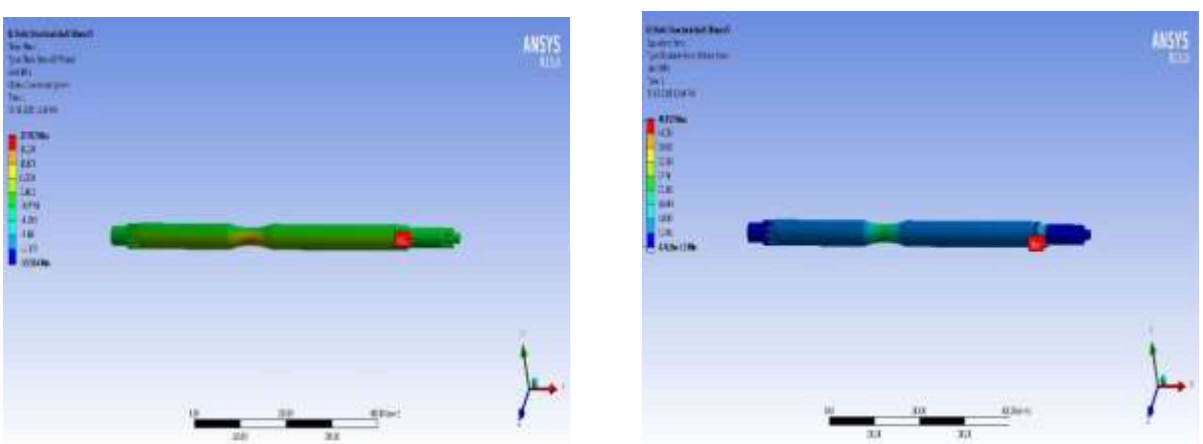


Figure 3. Stress analysis of 20MnCr5.



Comparative Analysis: Aligning Analytical and FEA Results

The core of the methodology lies in the direct comparison of the analytical results with those obtained from the ANSYS FEA. As documented in the study, this comparison provided a strong validation for the design.

For the EN8 material, the analytical shear stress of 17.189 MPa was in exceptional agreement with the FEA result of 17.17 MPa. This very minor difference of 0.019 MPa, or approximately 0.11%, suggests that the simplified analytical model is robust and the design for EN8 is acceptable under the specified loading conditions.

The analysis for 20MnCr5 revealed a more nuanced finding. The analytical shear stress result of 17.17 MPa was lower than the ANSYS-derived value of 17.917 MPa. This difference of 0.747 MPa, or approximately 4.35%, highlights the significant contribution of FEA to the design validation process. The higher stress value from the FEA is not a contradiction but a more accurate representation of the component's behavior. It is highly probable that the ANSYS model, with its ability to account for geometric discontinuities, captured localized stress concentrations that the simple analytical formula could not. For instance, splines or keyways on the shaft create points of stress concentration that can lead to higher localized stress values than the theoretical average. Therefore, while both values are considered to be in "good agreement," the FEA result for 20MnCr5 provides a more realistic and conservative stress value for engineering consideration, underscoring the necessity of using advanced simulation tools for critical component design.

RESULTS AND DISCUSSION

Validation of Shaft Shear Stress Results

The core objective of the initial analysis was to validate the design of the PTO shaft by comparing theoretical calculations with simulation results. The findings confirmed a strong correlation between the two methodologies. The analytical and ANSYS results for both EN8 and 20MnCr5 were found to be in "good agreement," which serves as a foundational confirmation that the design is technically sound under the given load conditions. This dual-method validation approach strengthens confidence in the design's integrity.

Table 3. Shear Stress Comparison and Analysis.

Material	Shear Stress (Analytical Results, MPa)	Shear Stress (ANSYS Results, MPa)	Difference (MPa)	Percentage Difference (%)
EN8	17.189	17.17	0.019	~0.11%
20MnCr5	17.17	17.917	0.747	~4.35%

Material Performance Comparison: EN8 vs. 20MnCr5

While both materials yielded acceptable stress values, the analysis clearly demonstrates that 20MnCr5 is the superior choice for this application. As established in the material analysis, 20MnCr5 possesses significantly higher ultimate tensile strength (1000 MPa) and yield stress (680 MPa) compared to EN8 (650 MPa and 465 MPa, respectively). These properties provide a greater margin of safety against static failure. However, the most compelling advantage of 20MnCr5 is its suitability for case-hardening. This heat treatment process, which creates a hard, wear-resistant surface while maintaining a tough core, is critical for the PTO shaft and gears, which are subjected to constant friction and surface contact. The superior wear resistance of 20MnCr5 ensures the component's longevity in the face of continuous operation.

Discussion on the Implications of the Shear Stress Findings for Overall Design Integrity

The validated shear stress values, which are well below the yield strengths of both materials, confirm that the design is safe from failure under a single static load. However, a PTO shaft in a mini-tractor operates under dynamic, cyclic loads throughout its service life. The primary concern for such a component is not static failure but fatigue failure, which occurs when cyclic stresses over a long period cause cracks and eventual breakage. While both materials may be technically "safe" based on the shear stress values, the superior properties of 20MnCr5, enhanced by the case-hardening process, provide a significantly higher endurance limit. This means the 20MnCr5 component can withstand a greater number of stress cycles before failure, leading to a much longer service life and greater reliability. Given that PTO systems are known to suffer from issues like clutch pack damage and wear from overloading, the choice of a highly durable material like 20MnCr5 is not a luxury but a fundamental requirement for meeting the customer's demand for a robust and low-maintenance product. Therefore, the findings not only validate the design but also provide a strong technical justification for selecting 20MnCr5 as the optimal material to ensure the product's long-term market success.

CONCLUSION

The proposed PTO drive-shaft assembly—comprising the helical gear, spur gear, and shaft—was evaluated using finite element analysis (FEA) in ANSYS 15. The numerical results obtained from the simulation were systematically compared with analytically derived values. This comparison confirmed that the computed stress distribution aligns closely with the theoretical calculations, indicating that the design satisfies established safety criteria.

Based on the outcomes of this investigation, it is further recommended that 20MnCr5 be selected over EN8 as the preferred material for PTO drive applications, owing to its superior performance characteristics under the evaluated loading conditions.

Future Work

By selecting a material with higher strength, the shaft can be designed to withstand maximum loading conditions while also enabling weight and cost optimization. In the present study, only the contact stress acting on the gear teeth has been evaluated. Future work may extend this analysis to include bending stresses on the teeth, supported by a comprehensive structural assessment. The analysis can be further expanded by examining the effects of varying module and face width to achieve an optimized gear design.

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