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A Topology Optimization Approach for Lightweight Design of CNC Tool Holder Assemblies

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Abstract - *Conventional CNC tool holders are typically overdesigned, leading to unnecessary weight, higher spindle loads, and reduced energy efficiency. This study focuses on the design and optimization of a BT40–ER32 CNC tool holder assembly through topology optimization and Design for Additive Manufacturing (DFAM) strategies to achieve lightweighting while preserving mechanical integrity. A redesigned collet nut incorporating a groove for chip deflector integration and dual-wrench operation was developed using SOLIDWORKS and structurally analyzed in ANSYS Workbench. Finite Element Analysis (FEA) was performed under realistic loading conditions—comprising preload, axial, radial, and tangential forces—to evaluate stress distribution, deformation, and safety factors. The optimized model achieved a 5.6% mass reduction relative to the conventional design, maintaining a safety factor above 2.2. A prototype was fabricated using Fused Deposition Modelling (FDM) to assess fit, functionality, and manufacturability. The outcomes demonstrate that targeted material removal and functional redesign can significantly improve performance, energy efficiency, and production sustainability. This research validates a complete digital workflow consistent with Industry 4.0 principles and sustainable manufacturing practices*

Key Words: **CNC Tool Holder, Topology Optimization, FEA, Lightweight Design, BT40-ER32**

1. INTRODUCTION

Computer Numerical Control (CNC) machines represent a cornerstone of modern manufacturing, offering automated and precise control over machining operations through pre-programmed computer commands. Compared to conventional manually operated machines, CNC systems deliver superior accuracy, repeatability, and productivity in material removal processes. Operating typically along three to five axes, these machines are capable of producing complex geometries with minimal human intervention [1-4]. In CNC milling, a rotating multi-point cutting tool removes material from the work piece as it follows programmed tool paths, enabling high-precision face milling, slotting, contouring, and pocketing operations. Similarly, CNC drilling employs rotating single-point tools to produce accurately positioned holes. Advanced process control features—such as adaptive feed rate adjustment, spindle speed modulation, and optimized tool paths—further enhance cutting efficiency while ensuring dimensional precision [5-7]. The performance and reliability of these machining operations depend significantly on the rigidity, concentricity, and balance of the tool-holding assembly. Even minor deviations in tool alignment or excessive vibration can lead to poor surface finish, accelerated tool wear, and geometric inaccuracies [8-10]. Consequently, the design of the tool holder and collet nut assembly plays a crucial role in ensuring smooth force transmission between the spindle and the cutting tool, thereby maintaining dynamic stability during high-speed machining [11-13]. Within the framework of Industry 4.0, CNC machining has evolved toward greater integration of optimization, automation, and digital twin technologies to improve process reliability, energy efficiency, and material utilization. Recent research efforts have increasingly focused on developing lightweight, high-stiffness, and dynamically stable tool holders using computational analysis and topology optimization techniques. Such advancements contribute to sustainable manufacturing by enhancing performance while minimizing energy consumption and material waste [14,15]. Among the various standards, the BT40 tool holder is one of the most widely used configurations in modern CNC machining centres due to its balanced design and suitability for high-speed operations. When combined with the ER32 collet system, it offers versatile clamping capabilities across a range of tool diameters while maintaining high concentricity and stability. Optimization of this tool holder assembly—particularly through topology optimization and additive design—presents a promising pathway for improving machining accuracy, extending tool life, and achieving overall process efficiency in advanced manufacturing environments [16,17]. In conventional CNC tool holders, excess material in non-critical zones leads to unnecessary weight, resulting in higher rotational inertia that negatively impacts spindle acceleration, dynamic balance, and overall energy efficiency. For high-speed machining applications, achieving an optimal stiffness-to-weight ratio is essential to minimize vibration and deflection during operation. By applying Design for Additive Manufacturing (DFAM) principles in combination with topology optimization, tool holders can be re-engineered to remove low-stress regions while maintaining the required structural integrity [18,19]. The optimized BT40–ER32 tool

holder, characterized by reduced mass and enhanced rigidity, contributes to improved machine dynamics, lower energy consumption, and increased overall productivity.

2. OBJECTIVES

This research focuses on improving the efficiency of CNC machining by optimizing a BT40–ER32 tool holder using topology optimization and FEA techniques to achieve weight reduction, enhanced stiffness, and energy efficiency while maintaining structural integrity and functional performance under real machining conditions. The main objectives are

- To develop and optimize a BT40–ER32 CNC tool holder aimed at achieving significant weight reduction through topology optimization techniques.
- To conduct comprehensive Finite Element Analysis (FEA) under realistic operating conditions, including preload, axial, radial, and tangential loading scenarios.
- To analyze and compare the stress distribution, deformation behavior, and factor of safety between the conventional and optimized tool holder models.
- To propose design enhancements that minimize material usage while preserving structural stiffness and functional integrity.
- To incorporate a groove-based feature for chip deflector integration, improving chip evacuation efficiency and enhancing tool safety during machining operations.

3. METHODOLOGY

3.1 Creation of Standard Design

A baseline model of the BT40–ER32 CNC tool holder assembly was developed (Fig.1) using standard industrial dimensions in accordance with ISO 7388-1 specifications. The model comprised the BT40 taper shank, ER32 collet chuck, and the corresponding collet nut. This reference design was created to study the structural performance, mass distribution, and areas of stress concentration in the existing configuration. All critical functional surfaces—such as the spindle taper, flange, and collet seating—were retained to preserve dimensional accuracy and ensure full compatibility with standard CNC spindle systems.

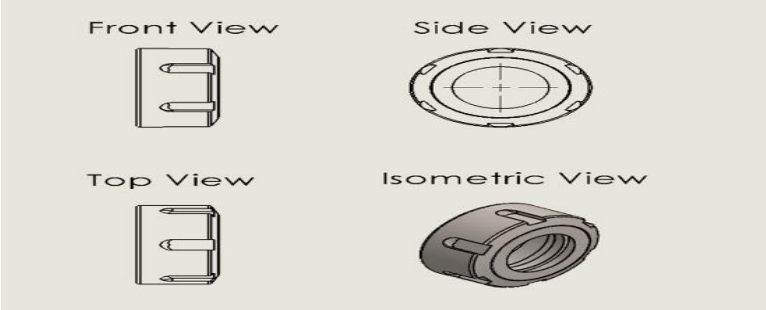

Fig -1: Standard Design

3.2 Development of Modified

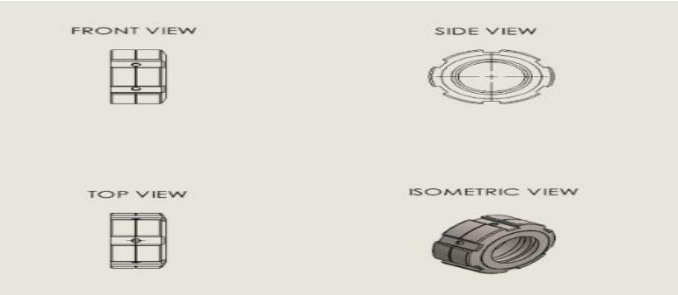

Fig -2: Modified Design

An improved version of the standard tool holder design (Fig.2) was created by incorporating both structural and functional upgrades. The collet nut was modified to include:

• A circumferential groove on the outer surface for direct attachment of a chip deflector, facilitating efficient chip removal during machining.

• A dual-wrench cavity arrangement, allowing compatibility with both U-type (UM) and C-type wrenches to enhance ease of use and accessibility.

• Subtle geometric adjustments in non-critical areas to reduce weight slightly while maintaining overall structural balance.

3.3 Assembled Prototype

All components of the BT40–ER32 tool holder assembly—including the holder body, collet, collet nut, and the newly added chip deflector—were virtually assembled using the SOLIDWORKS Assembly Module (Fig.3) . Each part was individually modelled with precise dimensions, tolerances, and alignment features to ensure accurate fit and interface during assembly.

Mating constraints such as concentric, coincident, and distance mates were applied to replicate the real-world assembly configuration. The collet was positioned concentrically within the tool holder taper, while the collet nut was aligned using the thread reference axis to guarantee proper engagement. The chip deflector was attached to the circumferential groove on the collet nut through concentric and offset mates, accurately representing its seated and symmetric orientation.

The virtual assembly process enabled verification of fit, alignment, and clearance among components prior to manufacturing. Interference detection and motion analysis were conducted to confirm that the deflector and wrench features did not obstruct spindle or tool movements. Finally, the complete model of the modified BT40–ER32 tool holder (Fig.4) with the integrated chip deflector was rendered for visualization.

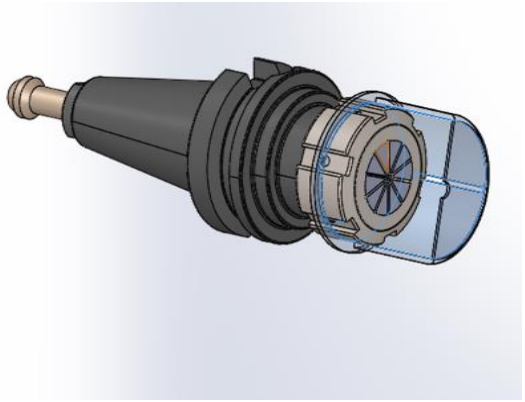

Fig -3: ER32 Collet System (Tool Side)

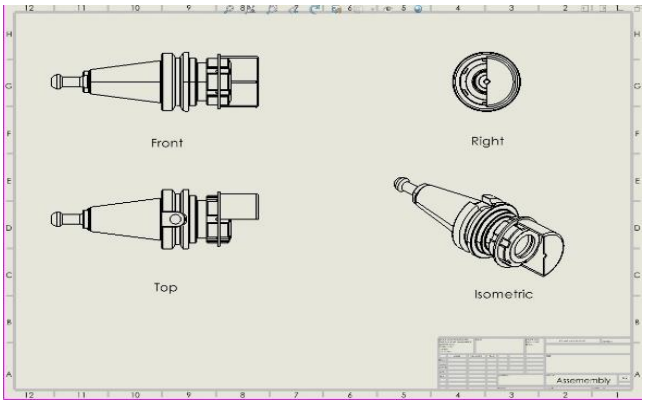

Fig - 4: ER32 Collet System (Machine Side)

3.4 Finite Element Analysis

Finite Element Analysis was performed using ANSYS Workbench to evaluate the mechanical performance of the modified design under realistic operating conditions. Material used is Stainless Steel and its properties are given in table.1.

Table 1 Stainless Steel Properties

Table -1: Stainless Steel Properties

Property	Symbol	Value	Unit
Young's Modulus	E	200×10^3	MPa
Poisson's Ratio	ν	0.3	–
Density	ρ	7850	kg/m^3
Yield Strength	σ_y	800	MPa
Ultimate Tensile Strength	σ_u	1000	MPa

- Meshing: Fine meshing was applied at critical stress concentration zones such as the groove root, wrench cavity, and flange fillets. Mesh element size was 2 mm.
- Boundary Conditions:

1. Preload Condition forces:

Assumptions:
Tightening torque, T = 105 N·m, Nominal thread (or equivalent clamping) diameter,
d = 40 mm = 0.04 m
Torque–tension relationship: where: T = Tightening torque (N·m)
F = Preload or clamping force (N), d = Nominal diameter N·m, K = 0.18 (Assume for nut factor)

Formula: $T = K * F * d$

Substitute values:

$$F = 105/(0.180.04)$$
$$F = 105/0.0072$$
$$F = 14538.33 = 15000\ N$$

The flat rear face of the nut was fixed in translation to simulate spindle constraint

2. Operational forces Conditions:

The chosen operational loads (Fa, Fr, Ft) were validated using empirical cutting-force estimation formulas from conventional milling operations. These formulas relate specific cutting force (Kc) to cutting geometry and feed parameters.

Assumptions:
• Tool diameter (D): 10 mm
• Axial depth of cut (ap): 2.0 mm
• Width of cut (ae): 10.0 mm
• Feed per tooth (fz): 0.05 mm
• Number of teeth (z): 2
• Average chip thickness (t_avg): fz / 2 = 0.025 mm
• Specific cutting coefficient (Kc): 3400 N/mm^2 (for hardened steel or aggressive cutting)

Tangential force (Ft) is calculated as:

$$Ft = Kc \times z \times t_avg \times ae$$

Substitute values: $Ft = 3400 \times 2.0 \times 0.025 \times 10 = 1700\ N$
The tangential force value (Ft = 1700 N) obtained aligns with realistic cutting loads for small-diameter end milling of steel.

Other force components are derived from empirical ratios commonly used in machining analysis:
• Radial Force, $Fr \approx 0.6 \times Ft = 0.6 \times 1700 = 1020\ N \approx 1000\ N$
• Axial Force, $Fa \approx 0.35 \times Ft = 0.35 \times 1700 = 595\ N \approx 600\ N$
Thus, the applied boundary conditions—Fa = 600 N, Fr = 1000 N, Ft = 1700 N—are justified by fundamental cutting mechanics. These forces represent typical load magnitudes acting on the collet nut under dynamic spindle operation during moderate-to-heavy cutting.

Axial force (Fa) = 600 N, Radial force (Fr) = 1000 N, Tangential force (Ft) = 1700 N

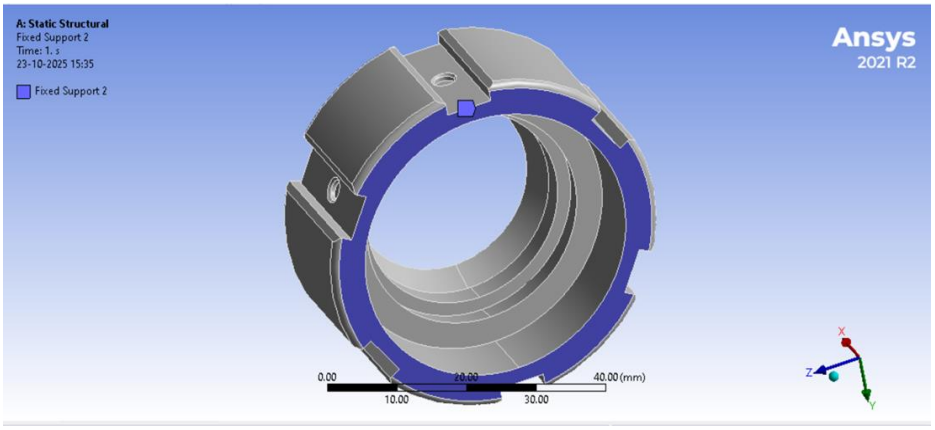

Fig -5: Fixed Support

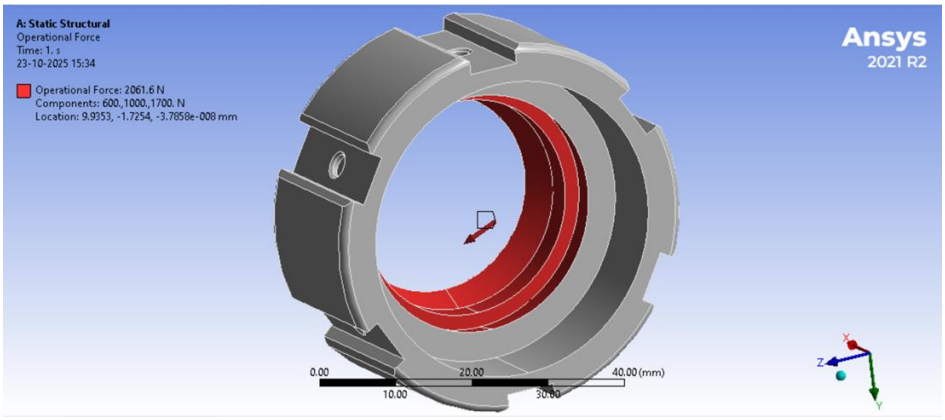

Fig -6: Preload and Operational forces

3.5 Validation through 3D Printing (FDM Process)

To physically validate geometry and assembly, the optimized collet nut was planned for prototype manufacturing using Fused Deposition Modelling (FDM). The 3D model was exported in STL format and printed using PLA filament with 0.2 mm layer height and 20% infill. The printed prototype serves as a fit and form validation model, allowing inspection of:

- Chip deflector mounting groove alignment
- Wrench engagement clearance
- Overall dimensional accuracy and handling comfort

Fusion 360 was used to simulate the 3D models for additive manufacturing (Fig.7 and Fig.8).

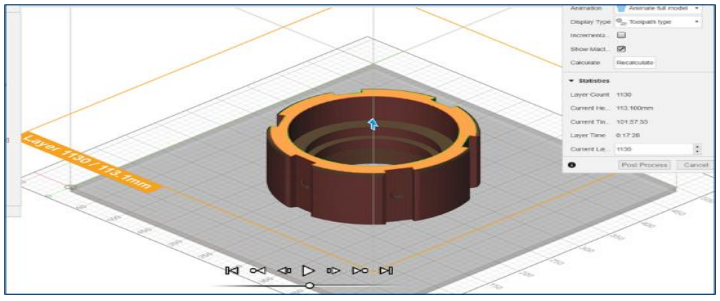

Fig -7: Simulation for FDM

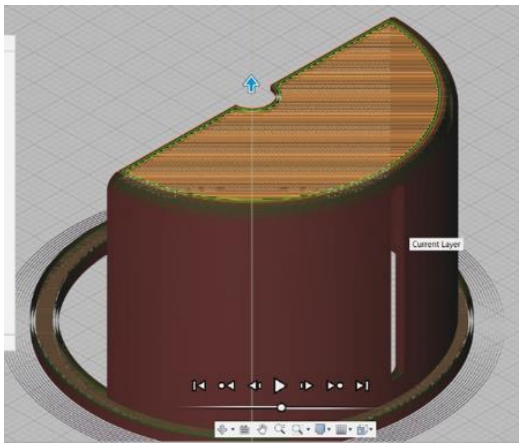

Fig -8: Simulation of Chip Deflector

4. RESULTS AND DISCUSSION

The Finite Element Analysis was performed on the BT40–ER32 collet nut for different design stages — the baseline design, manually optimized design, topology-optimized concept, and the final manually optimized design with groove and wrench cavity modifications. The results were evaluated based on stress distribution, total deformation, volume, and factor of safety. The key performance metrics are summarized in Table 2 given below.

Table -2: Stainless Steel Properties

Metric	Unit	Old Design (Baseline)	Manually Optimized (Iteration 1)	Topology Optimized (Iteration 2)	Final Manual Design
Yield Strength	MPa	250	250	250	250
Max Stress	MPa	95.823	109.74	Fails	112.44
Factor of Safety (FoS)	Ratio	2.61	2.28	-	2.22
Volume (V)	mm^3	20501.88	19395.25	12553.00	19382.66
Mass (M)	g	158.9	150.3	97.285	150
Deformation	mm	0.011042	0.0043772	Fails	0.011867

The comparative analysis shows that the final manually optimized collet nut design achieved a significant reduction in volume and mass compared to the baseline model. The optimized nut weighs approximately 5.6% less than the standard design, contributing to lower spindle load and improved dynamic balance during machining operations.

Despite the incorporation of additional features such as the chip deflector mounting groove and dual-wrench cavity, the stress levels remained within safe limits. The maximum von Misses stress observed in the final design was 112.44 MPa, well below the yield strength of 250 MPa for stainless steel. The Factor of Safety (FoS) of 2.22 indicates adequate structural integrity under combined preload and operational forces.

The total deformation in the final design was 0.0119 mm, which is negligible in comparison to the functional tolerance range of collet assemblies. This confirms that the deflection of the nut under load will not affect clamping precision or tool alignment.

The stress concentration zones were predominantly located near the outer groove edges and flange–thread transition region. This was expected due to geometric discontinuities, but remained below critical thresholds, proving that the added groove does not compromise performance.

In terms of mass efficiency, the final design achieved near-identical stiffness and safety compared to the baseline while integrating new functional capabilities (chip deflector mounting and dual wrench compatibility). The results validate the design modification approach and demonstrate the feasibility of lightweight optimization without reducing structural safety.

After applying the supports and boundary conditions,

Total Deformation under Operating Load: The colour gradient maps the displacement magnitude, highlighting the load path through the component (Fig.9). The blue zones show minimal movement at the taper interface (the constrained end), while the gradient shifts to red zones at the free end (the collet face). This confirms the expected cantilever beam behaviour of the tool holder and proves that the taper section is rigidly held by the spindle.

First Principal Stress Distribution: Comparing the Principal Stress to the Von Misses Stress plot shows that the critical high-stress region is consistent across both analyses (Fig.10). The low stress values across the entire taper section and the flange (the blue zones) indicate that the material removal achieved via optimization has not created any unexpected or large areas of high tensile weakness, confirming the structural stability of the design.

Von Misses Equivalent Stress Distribution: The stress contour map clearly illustrates the efficiency of the optimization process (Fig.11). The majority of the tool holder body (represented by the blue and green zones) experiences low-to-moderate stress, confirming that material removal was primarily concentrated in non-load-bearing regions. The high-stress red zone is well-managed and localized to the fillet, indicating no widespread structural weaknesses were introduced by the weight reduction.

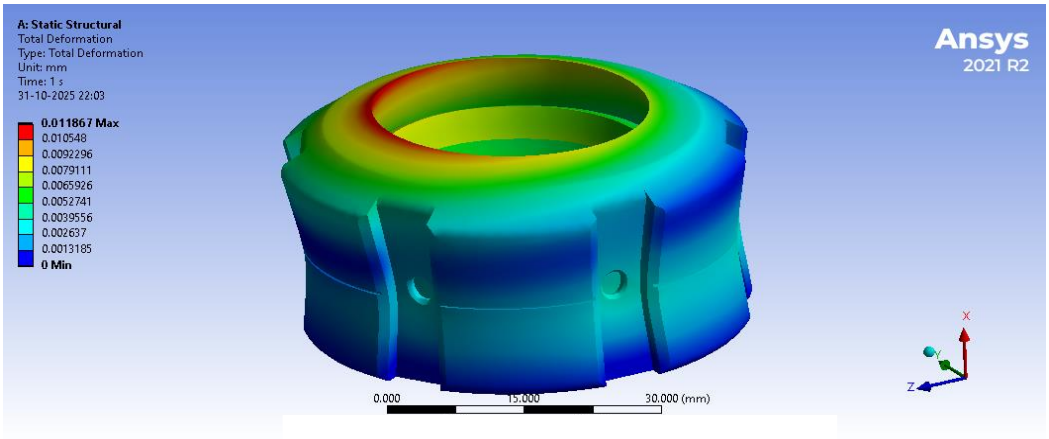

Fig -9: Total Deformation

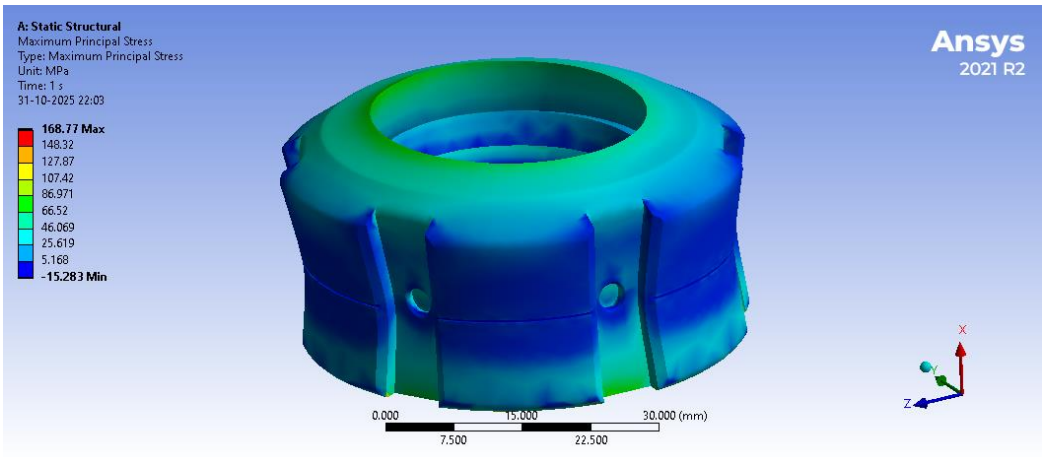

Fig -10: Maximum Principal Stress

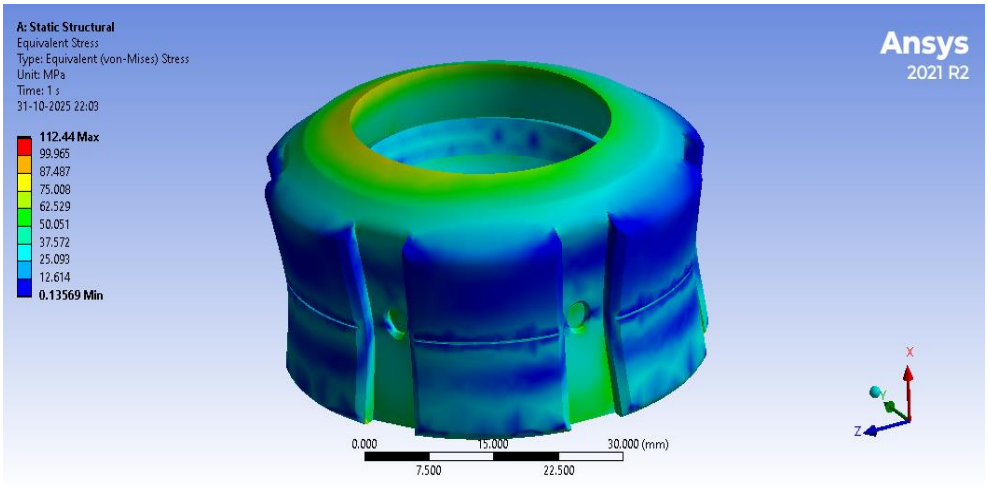

Fig -11: Equivalent Stress

5. CONCLUSION

The study demonstrates that the modified BT40–ER32 tool holder with an integrated chip deflector groove is both structurally sound and suitable for manufacturing. The optimized design achieves a reduction in volume and mass, thereby improving spindle efficiency, dynamic balance, and overall performance. Finite Element Analysis confirms that the resulting stress and deformation values remain well within the acceptable limits for stainless steel, ensuring structural integrity and precision. Moreover, the introduced functional enhancements provide additional usability benefits without compromising mechanical strength or accuracy. Future work will focus on experimental validation through 3D-printed prototypes and subsequent trials using metallic versions to further confirm the design's practical viability.

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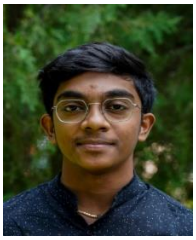

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