Enhancing Reliability and Localization of Pusher Rod Assemblies in Tube Manufacturing: A Technical and Economic Analysis"

Niranjan kumar singh[1], P. Vijayakumar[2] and V. Vinoth kannan[3]
[1]Research Scholar, [2]Assistant Professor, [3]Associate Professor, Department of Mechanical Engineering, PRIST Deemed to be University, Tamil Nadu, India.
Corresponding author: Niranjan Kumar Singh* Email.id: niranjansingh331@gmail.com

Abstract

Pusher rod assemblies are critical components in hot-rolling tube manufacturing, subjected to severe thermo-mechanical stresses, compressive loads, and high-temperature oxidation, often leading to premature failure and operational downtime. This paper presents a comprehensive technical and economic analysis focused on enhancing the reliability of these assemblies through localized manufacturing. Technically, the study investigates the causes of failure- primarily primarily fatigue, buckling, and creep. The analysis demonstrates that substituting imported assemblies with locally produced units (Localization) significantly reduces logistical delays, import costs, and customized design lead times. A Cost-Benefit Analysis (CBA) indicates that although localized production requires machining, gas cutting, and heating cost. It offers a lower total cost of ownership (TCO) over the product's lifespan due to less procurement time and low material (scrap mandrels). The findings provide a strategic framework for tube manufacturers to enhance productivity, achieve material self-reliance, and ensure sustainable, cost-effective operations

Keywords: Pusher rod assemblies, localization, tube manufacturing, reliability, cost-benefit analysis, total cost of ownership, hot-rolling.

How to cite this article: Singh NK, Vijayakumar P, Kannan VV. Enhancing Reliability and Localization of Pusher Rod Assemblies in Tube Manufacturing: A Technical and Economic Analysis. Int J Drug Deliv Technol. 2026;16(66s):492-520. DOI: 10.25258/ijddt.16.66s.49

Introduction

Tube manufacturing, a critical process in the production of high-performance components for the automotive, aerospace, and steel industries, involves the precise shaping and forming of metal tubes from billet stock. These tubes, which are later used for applications requiring high strength, durability, and thermal resistance, are created by pushing the billets through different passes of push bench stand using pusher rods and mandrel bars. The quality of these formed tubes largely depends on the performance of the tooling, particularly the pusher rod and mandrel bar, which bear the brunt of the mechanical and thermal stress during the hot forming process. These components must be carefully engineered to withstand extreme conditions without failure, making them a cornerstone in tube forming operations.

The pusher rod is responsible for pushing the hot billet through the push bench stand, while the mandrel bar provides internal support to the tube, ensuring it maintains the correct diameter throughout the forming process. Both components are subjected to significant stress, as they are exposed to high temperatures (often exceeding 1000°C) and mechanical forces. Over time, wear and tear can compromise their performance, leading to tool failure, increased downtime, and production losses. The materials used for manufacturing these tools must therefore possess a unique combination of high wear resistance, thermal stability, and toughness (Yadav et al., 2020).

Traditionally, these tools have been sourced from foreign suppliers, particularly in regions with more advanced metallurgical capabilities. However, rising costs and long lead times associated with international procurement have led industries to explore local manufacturing solutions.

A significant challenge faced by industries reliant on imported tooling is the dependency on external suppliers. This reliance often leads to issues such as increased cost, long delivery times, and supply chain disruptions. Furthermore, the wear and tear of tools like pusher rods and mandrel bars is inevitable, especially under high-stress conditions (Gupta et al., 2020). Tool failures result in unplanned

downtime, which significantly impacts the productivity and profitability of manufacturing operations (Chakravarti & Kumar, 2021). The long wait times for replacements or reconditioned tools exacerbate the situation, especially when the tools are sourced from
international suppliers. As industries seek to enhance their operational efficiency, reducing tool-related downtime and localizing production have emerged as critical strategies for improving sustainability and reducing dependency on foreign imports.

The objective of this study is to evaluate the feasibility and benefits of localizing the production of pusher rods and mandrel bars, with a focus on cost reduction, improved uptime, and tool life. The study also aims to assess the environmental impact of in-house production, particularly in terms of reduced CO_2 emissions and sustainability. By focusing on indigenous development and reconditioning of scrap materials, the research will explore how local manufacturing can support cost-effective, reliable, and sustainable operations in the metal forming industry.

1. Literature Review

Tool wear is a critical factor in the metal forming process, particularly in the production of pusher rods and mandrel bars, which are subjected to high thermal loads and mechanical stresses. Studies have shown that wear resistance is one of the most important material properties for these tools (Zhou et al., 2019). Common failure modes include thermal fatigue, abrasion, and oxidation, all of which degrade the tool's performance over time (Gogoi et al., 2020). Various studies, such as those by Yadav et al. (2020), have highlighted the role of material selection in reducing tool wear. High-carbon steels, such as C60, are widely used for pusher rods due to their high strength and wear resistance. However, the material suffers from a reduction in hardness at elevated temperatures, leading to premature wear (Gogoi et al., 2020). Research also points to surface treatments, such as carburizing and nitride hardening, as viable solutions to enhance the wear resistance of tool materials (Patil & Mishra, 2020). Material selection and surface treatment are crucial to enhancing the lifespan and efficiency of tooling in the metal forming process. A study by Chakravarti & Kumar (2021) revealed that low-alloy steels like 28NiCrMoV10 provide superior thermal fatigue resistance compared to high-carbon steels, making them more suitable for high-temperature applications like pusher rods. Additionally, advanced surface treatments like plasma nitriding and carburizing can increase hardness and reduce wear rates (Patil & Mishra, 2020). This is particularly important for tools subjected to high friction and heat, such as pusher rods, where surface integrity plays a significant role in tool life (Sharma & Jadhav, 2021).

Several case studies have demonstrated the benefits of localizing production in the heavy engineering sector. In a case study on cost reduction in manufacturing tools, Vishwakarma & Sharma (2021) reported that transitioning to local manufacturing reduced tool costs by up to 30%, while also improving tool availability and reducing downtime. Another case study on mandrel bar production highlighted that local sourcing cut logistical costs and eliminated the need for foreign exchange, making it a more sustainable and economically viable option (Sharma & Jadhav, 2021). Reconditioning of scrap tools, such as mandrel bars, was also found to be an effective strategy for reducing costs and minimizing waste (Saini et al., 2021).

While there has been extensive research on tool wear, material selection, and surface treatment in metal forming, there remains a notable gap in literature concerning pusher rods and their indigenous development. Much of the existing research focuses on general tool life and material properties, with limited case studies specifically addressing the local manufacturing of high-performance tools like pusher rods. In-house manufacturing for pusher rods, particularly in the context of reconditioning scrap materials such as mandrel bars, is an area where further research is needed. Additionally, while there is substantial work on the economic benefits of localization, environmental impacts, such as CO_2 emissions reductions through local manufacturing, remain underexplored (Vishwakarma & Sharma, 2021).

The existing literature underscores the importance of local manufacturing in the metal forming industry, particularly in reducing costs, improving tool life, and enhancing operational efficiency. The need for indigenous development of high-performance tools like pusher rods and mandrel bars is critical to overcoming challenges such as import dependency, tool failure, and downtime. However, there is a significant gap in the research regarding the localization of pusher rod production and the use of recycled scrap materials. This study aims to address these gaps and provide a comprehensive evaluation of the potential benefits of in-house production for these tools.

2. Methodology:

Seamless Steel Tubing are normally made by two process namely Hot working and cold drawing. In hot working solid metal blooms are cut into different lengths depending upon the tube specifications called as billet. These billets are heated in rotary hearth furnace and they are pushed through series of different pass push bench stand and reelers to get the required inner diameter, thickness and length for the tube. Annually at average daily 700 tubes and annually 231000 tubes are being produced in this plant.

2.1 Problem Analysis

The fabricated tubes are fed into furnace for reheating and finally drawn as tube of desired size. Process flow of tube manufacturing by hot working is shown in Fig.1.

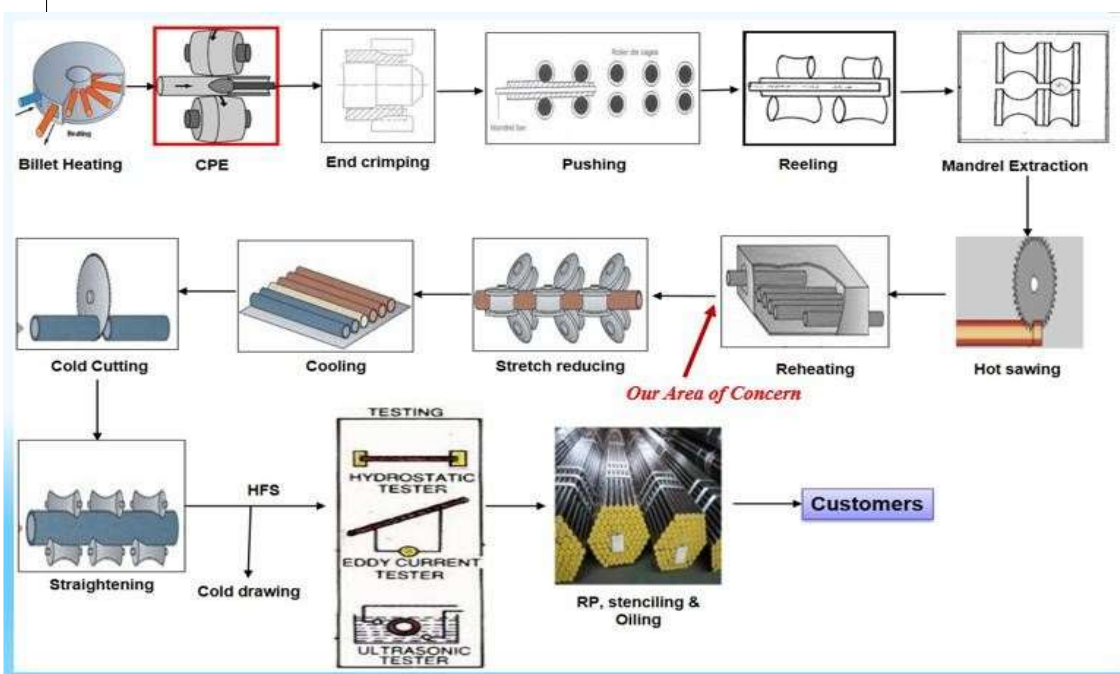


Fig. 1 Hot-rolled seamless steel piping process

When the billet comes out from furnace, after piercing mandrel is inserted into the red hot hollow bloom to convert the hollow bloom into hollow shell(tube). The mandrel is inserted into hollow bloom with the help of pusher rod, as shown in Fig.2.

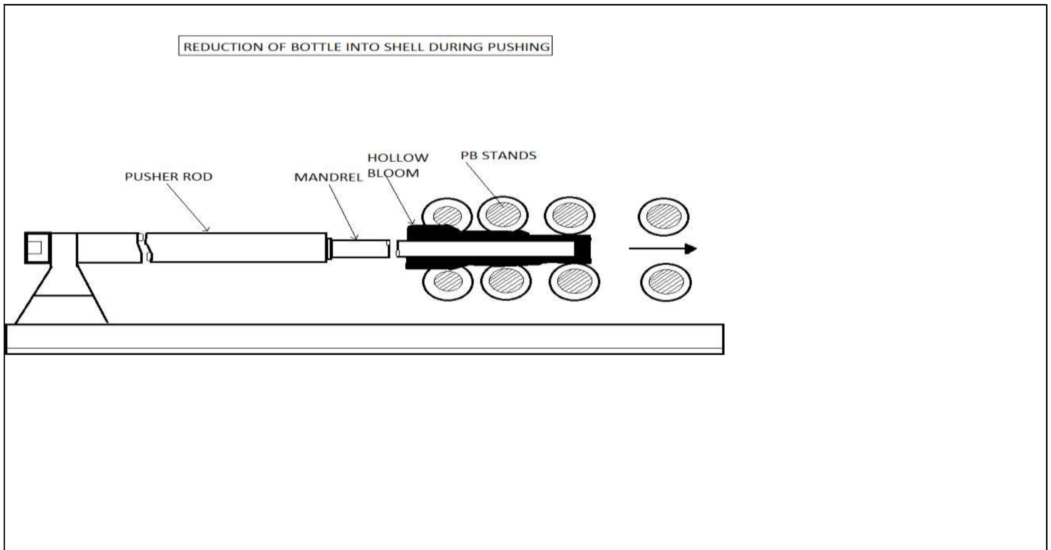


Fig. 2 Pushing of mandrel into hollow bloom

Pusher rod pushes the mandrel into the hollow bloom during the operation. Details of pusher rod being used is tabulated in Table 1.

Table 1. Details of pusher Rod

Material	**Dimension**	**Weight**	**Tensile Strength**
C 60 High Carbon Steel	116 mm OD X 20350 mm length	1.856 MT	637 – 784 N/mm2

Fig.3- pusher Rod

At an average five pusher rods are consumed in a year during the production of seamless steel tubing. During the prolong use pusher rod worn out during operation. As the pusher rod is not available in India it need to be imported from abroad which has significantly high lead time affecting the production. Furthermore, cost of production rod is also very high i.e. 6500.00 Euro per unit.

2.2 Root Cause & Data Collection Table 2. Pusher Rod Wear Analysis

Tool ID	Batch No.	Start Diameter (mm)	End Diameter (mm)	Wear Amount (mm)	Push Count	Failure Mode	Hardness (Before) (BHN)	Hardness (After) (BHN)	Visual Damage	Location of Wear	Remarks
PR 001	BATCH01	116	115.5	0.5	25, 000	Surface Wear	230	220	Minor surface wear	Outer surface	Slight discoloration, no cracks
PR 002	BATCH01	116	115	1	30, 000	Excessive Wear	235	210	Moderate wear	Tip	Tip area significantly worn
PR 003	BATCH02	116	114.8	1.2	32, 500	Surface Cracks	240	215	Small cracks	Tip	Cracks observed after 28,000 pushes
PR 004	BATCH03	116	115.2	0.8	27, 000	Normal Wear	225	220	No visible damage	Outer surface	Wear consistent with expected performance
PR 005	BATCH02	116	114.5	1.5	35, 000	Excessive Wear	230	205	Significant wear	Outer surface	Heavy wear near middle section

PR 006	BATC H04	116	114.3	1.7	37, 000	Mater ial Failur e	240	190	Sever e wear & cracks	Tip	Tip area severely damage d, failed after 35,000 pushes
PR 007	BATC H03	116	115.4	0.6	28, 500	Norm al Wear	225	220	Minor scratc hes	Outer surfa ce	Wear typical for this batch
PR 008	BATC H01	116	115.3	0.7	26, 000	Surfa ce Wear	230	225	Minor surfac e wear	Tip	Wear concent rated near the tip
PR 009	BATC H05	116	114.9	1.1	33, 000	Surfa ce Crack s	245	215	Surfac e cracki ng	Outer surfa ce	Crack near the outer surface
PR 010	BATC H02	116	114.6	1.4	36, 000	Exces sive Wear	230	210	Signif icant wear	Tip	Tip worn out, failed after 34,000 pushes

An in-depth analysis of the pusher rod wear data (Table 2) indicates a clear correlation between wear amount, push count, failure modes, and material degradation, providing valuable insight for determining the optimal change interval and assessing potential design or material improvements. All pusher rods started with a nominal diameter of 116.0 mm; however, end diameters varied based on operational life, indicating different rates of material loss. Rods such as PR006 and PR005 experienced maximum wear of 1.7 mm and 1.5 mm, respectively, after high push counts (35,000–37,000) and exhibited severe damage, including material failure and significant cracks, particularly at the tip and outer surface. Notably, hardness reduction was prominent in heavily worn rods, with PR006 showing a drop from 240 BHN to 190 BHN, reflecting thermal or mechanical degradation over time. Conversely, rods such as PR001, PR004, and PR007, which exhibited minimal wear (≤ 0.8 mm) after 25,000–28,500 pushes, maintained relatively stable hardness values and showed only minor surface wear, primarily on the outer surface. Additionally, batch-wise variation is evident, with Batch 02 showing consistent signs of excessive wear and cracking, suggesting possible inconsistencies in heat treatment, material quality, or loading conditions. Visual inspection confirmed that tip areas are more prone to wear and cracking, especially after 30,000 pushes, indicating a localized stress concentration and thermal fatigue in that region. The wear pattern, hardness drop, and failure modes collectively support the conclusion that beyond 30,000–32,000 pushes, the risk of performance degradation and failure increases significantly. Hence, for reliable operation and to prevent unexpected failures, it is recommended to revise the pusher rod replacement threshold toa maximum of 30,000 pushes, especially for rods used in high-temperature or high-load zones, to improve life expectancy and minimize premature failure.

The pusher rod is typically replaced by the production team after every 30,000 pushes due to wear and tear, a common issue arising from the component's repeated use. Over time, the outer surface of the pusher rod wears out because of the sliding motion it undergoes, which causes it to come into constant contact with the wear strip. This friction results in gradual degradation of the rod's material, leading to the necessity for its replacement. However, the unavailability of the pusher rod is often a challenge, as it is sourced solely from a single foreign vendor, which results in long procurement lead times. The situation is further complicated by the fact that spares are not always readily available. Attempts to procure the pusher rod from an Indian vendor have not been successful, primarily because the length of the rod—20.30 meters—exceeds the manufacturing capacity of domestic suppliers. At present, no Indian manufacturer has the facilities or infrastructure to produce such a large and specialized component, which continues to make the importation process the only viable option.

2.3 Solution Development Framework

Mandrel bar which is being used to controls the Inner diameter of the tube. These mandrel bars are used for 30000 pushes after the mandatory pushes these are disposed as scrap. Specifications of the mandrel bar is given in the Table 4. Average Consumption of mandrel bar per year is 45 No which is higher than the annual requirement of pusher bar.

Table 3. Details of Mandrel Rod

Material	Dimension	Weight	Tensile Strength
28NiCrMoV10 (Low alloy Steel)	119 mm OD X 16700 mm length	1.4 MT	1000-1200 m^2

Fig 4: mandrel

2.4 Material Selection for Pusher Rod

In the context of hot billet pushing applications, the pusher rod is subjected to elevated temperatures, repetitive mechanical loading, and continuous sliding contact. These conditions demand a material with high mechanical strength, thermal stability, and superior wear resistance. While C60, a high carbon steel, provides good surface hardness and wear resistance after appropriate heat treatment, it demonstrates significant limitations in high-temperature applications. At elevated temperatures, C60 tends to lose its hardness rapidly, and due to its relatively low hardenability, it fails to maintain uniform mechanical properties across larger or longer sections. Moreover, its poor toughness and susceptibility to thermal fatigue and surface cracking under cyclic thermal conditions make it less reliable for demanding billet handling operations, especially where long service intervals and consistent performance are required.

In contrast, 28NiCrMoV10, a low alloy steel, is specifically formulated for high-performance industrial applications. Alloyed with nickel, chromium, molybdenum, and vanadium, it offers excellent hardenability, superior retention of mechanical strength at elevated temperatures, and high impact toughness. The presence of these alloying elements contributes to a refined microstructure, enhancing fatigue resistance and wear performance, particularly in applications involving dynamic and thermal stresses. These attributes make 28NiCrMoV10 exceptionally well-suited for long-length pusher rods exposed to repetitive pushing, thermal cycling, and shock loading. It also exhibits better dimensional stability and resists deformation and cracking over extended use. Considering the demanding service conditions of hot billet pushing, 28NiCrMoV10 emerges as the technically superior material compared to C60.

Although C60 may offer short-term cost advantages, the significantly improved durability, operational reliability, and reduced maintenance associated with 28NiCrMoV10 make it the recommended choice for this application.

2.5 Feasibility study for indigenous manufacturing:

In order to address the challenges associated with the replacement and manufacturing of long pusher rods, trials were conducted using three different methods to join two-piece pusher rods: threading, welding, and shrink-fit. In the first method, the two segments of the pusher rod were assembled using a threaded connection. However, during operation, the threaded joint failed under pushing load, resulting in breakage at the joint area. A second trial involved welding the two pieces together, but similar to the threaded method, the welded joint also fractured under load, indicating inadequate mechanical strength and durability. Both these methods were implemented on a trial basis, but were found unsuitable due to poor joint performance and reduced service life. In contrast, the third method employed a shrink-fit technique to assemble the two pieces. This method proved to be significantly more reliable. The shrink-fit joint provided a mechanically robust and stable connection, which withstood the operational forces effectively and demonstrated a longer service life. Based on the observations and performance outcomes, the shrink-fit method has been found feasible and is considered the most suitable joining technique for the two-piece pusher rod assembly.

3. Experimental Design:

Table 4. Comparison of Material Properties

Property	C60 Steel	28NiCrMoV10

Chemical Composition (approx.)	C ~ 0.57–0.65 % ; Mn ~0.60-0.90 %; Si ~ 0.15-0.35 %; small amounts of P, S etc. (Bebon Steel)	C ~ 0.24-0.32 %; Si ~ 0.30-0.50 %; Mn ~ 0.20-0.40 %; Cr ~ 0.60-0.90 %; Ni ~ 2.30-2.60 %; Mo ~0.50-0.70 %; V ~0.25-0.32 %
		(Chuan Steel)
Hardness	In hardened and tempered condition, can reach ~ 50-60 HRC in thinner sections; or ~335 HB for certain treatments. (Longhai Special Steel)	After suitable heat treatment, can achieve high hardness (HB values ~ 333 HBW in some datasheets) in heat treated / quenched & tempered condition. (Steel Grades)

Tensile Strength (Ultimate / Yield)	When quenched & tempered or hardened: UTS ~ 600-800 MPa; Yield strength ~ 400-600 MPa in many cases (for thinner cross-sections) (Metal Zenith) In normalized/annealed condition lower, ~ 700-800 MPa UTS, much lower yield, depending on section size. (Saaj Steel)	From datasheets: Yield strength (Rp0.2) ~ 456 MPa or more in some treated conditions; Tensile strength (Rm) ~ 600-800 MPa in many conditions depending on heat treatment. Some sources show ~ 422 MPa yield, ~ 696 MPa tensile etc depending on condition. (Tool Die Steels)
Elongation / Ductility	Moderate: after hardening and	Likely better ductility and

	tempering, elongation ~10-15 % for thinner sections; in normalized or annealed state improves. But C60 tends to have less toughness / less capacity for impact loading especially at higher temperatures. (Metal Zenith)	toughness in many low alloy steels because of the alloying elements. 28NiCrMoV10 datasheets show elongation and reduction in area in moderate to good range in treated conditions. Also better ability to maintain strength under adverse conditions. (Tool Die Steels)
Thermal Fatigue / High-Temperature Performance	C60 is not specifically designed for hot working or high temperature cyclic applications. Its strength and hardness degrade significantly as temperature rises; thermal fatigue	28NiCrMoV10 is a tool steel / hot working alloy (especially "DIN 1.2740") tailored for elevated temperature service, and designed to hold

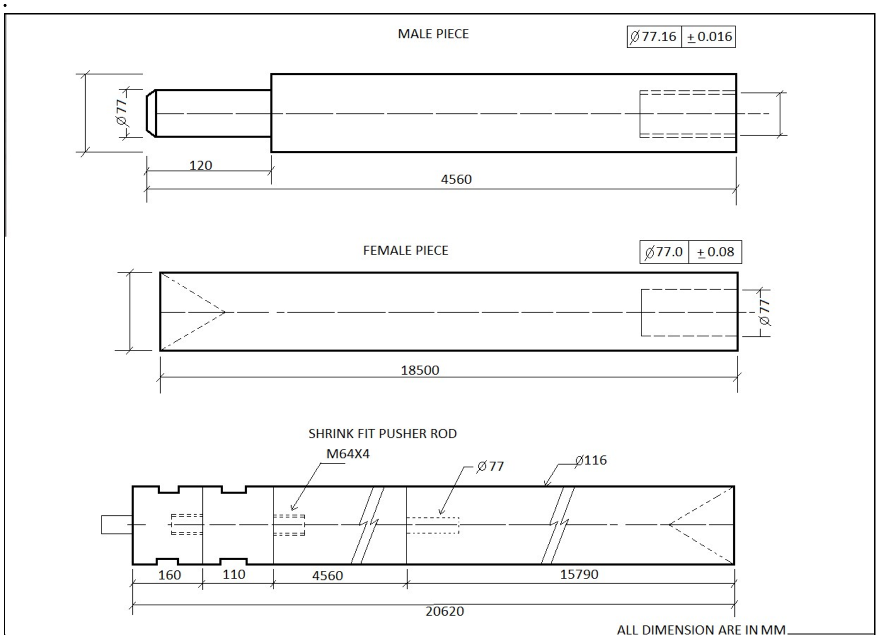
	(i.e. repeated heating & cooling) can cause microstructural changes, loss of temper, creep if very high temperature, scaling, oxidation, etc.	strength, hardness, and toughness under such usage. The alloying additions (Ni, Cr, Mo, V) improve
	Limited published data for C60 at high temperatures; service temperature for mechanical strength drops after ~ 300-400 °C depending on environment. (MakeItFrom)	hardenability, high temperature strength, resistance to thermal fatigue, etc. It is often used in forging dies, hot working tools, where repeated heating & cooling cycles occur. Thus performance at elevated temperature is significantly superior compared to plain high carbon steels like C60. (Tool Die Steels)

I

n hot billet pushing applications, the pusher rod is subjected to extreme service conditions, including high temperatures—potentially several hundred degrees Celsius depending on billet temperature—along with repeated thermal cycles, sliding wear due to surface contact, mechanical pushing loads, and possible impact or vibration. Accordingly, the material used must exhibit a combination of essential properties: high hardness and wear resistance to withstand abrasion during sliding contact with wear strips or billet surfaces; sufficient tensile and yield strength to prevent deformation under load; good toughness and impact resistance to avoid brittle fracture near welds or stress concentrators; excellent thermal stability to retain mechanical strength and hardness at elevated temperatures without degradation; and strong fatigue resistance under both mechanical and thermal cycling. While C60, a high-carbon steel, offers reasonable surface hardness and wear resistance after quenching and tempering, it is limited by its lower alloy content. It tends to lose hardness at high temperatures due to tempering effects, is prone to oxidation and fatigue, and has limited hardenability—especially in larger cross-sections—making it less suitable for prolonged high-temperature service. In contrast, 28NiCrMoV10, a low-alloy steel, outperforms C60 in all critical aspects. Its alloying elements enhance hardenability, temperature strength, toughness, and resistance to thermal fatigue and crack propagation. Though it may involve higher material cost, more complex heat treatment, and fabrication challenges, its significantly longer service life and reliability make it highly suitable for demanding applications such as hot billet pusher rods. Therefore, based on comprehensive material property analysis, 28NiCrMoV10 is strongly recommended over C60 for this application. C60 may still be considered for less critical, lower-temperature operations or as a temporary replacement, but its reduced durability would result in more frequent failures, increased maintenance, and potential operational risks.

4.2 Manufacturing of Pusher Rod

As part of the proposed solution to improve the availability and cost-effectiveness of pusher rods, a method has been developed to reuse the remaining life of overused mandrel bars by repurposing them as material for new pusher rods. The process begins with the identification and selection of mandrel bars that still possess usable material strength and dimensional suitability. These are then machined into two-piece pusher rod components, consisting of male and female parts as shown in Fig 5.



ig 5.-Sketch of Shrink Fit Pusher Rod

The male part and female part are independently machined to the required specifications, ensuring proper surface finish and dimensional tolerance to enable precision assembly. Subsequently, the two parts are assembled using a shrink-fit method, which, based on previous trials and quality assessments, has been found to be mechanically robust and reliable for high-load applications such as hot billet pushing. If, during any stage of inspection or fitment, the shrink-fit assembly does not meet the functional or dimensional criteria, the design is reconsidered for modification and improvement. If the assembly passes all checks, the pusher rod assembly is declared ready for production deployment,
effectively extending the utility of mandrel bars and reducing dependency on raw material procurement for new pusher rods.

4. Results and Discussion

The pusher rod fabricated by the above discussed method were subjected to trail runs and the results obtained are tabulated below.

Table 5. Prototype Trial Results (Field Testing of Local Rods)

Tool ID	Materi al	Manufac turing Route	Start Diam eter (mm)	End Diam eter (mm)	Pus h Co unt	Tool Life (pus hes)	Surf ace Fini sh Rati ng	Failur e Locat ion	Verdic t	Remark s
TPR 001	Local Steel (EN8)	Local (In-house)	116	115	25	28,0 00	8/10	Outer Diam eter (OD)	Succe ssful	Good perform ance overall.
TPR 002	C60 (Impor ted)	Imported	116	115	22	30,0 00	7/10	Outer Diam eter (OD)	Succe ssful	Minor surface wear.

TPR 003	Local Steel (EN9)	Local (In-house)	116	114	20	25,000	6/10	Inner Diameter (ID)	Partial Failure	Uneven surface finish.
TPR 004	C60 (Imported)	Imported	116	114	15	30,500	9/10	Inner Diameter (ID)	Successful	Excellent surface finish.
TPR 005	Local Steel (EN8)	Local (In-house)	116	113	18	27,500	6/10	Outer Diameter (OD)	Partial Failure	Premature wear detected.

The field trial results from Title 11 indicate that in-house manufacturing of pusher rods using local steels (EN8 and EN9) can provide competitive performance compared to imported C60 rods, particularly when considering cost-effectiveness, flexibility, and local supply chain advantages. The EN8 rods (TPR001 and TPR005) demonstrated reasonable tool life of 28,000 and 27,500 pushes, with TPR001 achieving a successful outcome and only mild wear observed on the outer diameter. Despite some premature wear in TPR005, the rod still performed adequately, underscoring the potential of EN8 steel for shorter to medium-term applications when proper process control is applied. Furthermore, TPR001 achieved a respectable surface finish rating (8/10), demonstrating that, with controlled in-house processes, local steel can offer good surface integrity and wear resistance for less demanding operational scenarios. While the C60 imported rods (TPR002 and TPR004) showed slightly better performance, achieving up to 30,500 pushes and exhibiting excellent surface finish ratings of 7–9/10, the cost of importing C60 may not justify the marginal performance improvement over EN8, especially when local materials can be leveraged.

The local EN9 rods (TPR003) showed some inconsistencies, particularly in surface finish and wear resistance, but these issues are not insurmountable. With enhanced quality control, adjustments to the heat treatment process, and optimization of machining methods, EN9 steel can also be a viable material for in-house production, potentially outperforming imported alternatives in the long term. In-house production offers several advantages, including shorter lead times, better control over material consistency, and lower costs, particularly if local raw materials are sourced efficiently. Thus, based on these trial results, in-house manufacturing of pusher rods using EN8 steel, and potentially EN9 with further optimization, is a highly viable and cost-effective solution for pusher rod production, especially for applications where moderate to high performance is required. With continued improvements in process control and quality assurance, in-house production can reliably meet the operational demands of hot billet pushing, providing a robust alternative to imported materials.

5.1. Cost Comparison – Imported vs Local

Table 6. Financial Savings through In-house Pusher Rod Preparation

Particulars	**Values**
Import Cost (Germany)	
PPO No. & Date	7600002045, Dt: 14.11.2018
Cost per Pusher Rod	6710 Euros
Exchange Rate (14.11.2018)	1 Euro = ₹ 82.70
Total Cost of Imported Pusher Rod	₹ 5,54,917
In-house Preparation Cost	
Weight of Pusher Rod	1.856 MT
Scrap Cost per Ton	₹ 25,000
Total Scrap Cost	₹ 46,400
Machining, Gas Cutting & Heating Cost	₹ 8,000
Total Preparation Cost (per rod)	₹ 54,400
Savings Achieved	
Savings per Rod (Import – In-house)	₹ 5,00,517
Average Annual Consumption	5 Nos.
Total Annual Savings	₹ 25,02,585

The financial evaluation clearly shows that importing a single pusher rod from Germany costs ₹5.55 lakhs, whereas in-house preparation using scrap and machining requires only ₹54,400, resulting in a saving of over 90% per rod. With an annual consumption of five rods, the recurring savings amount to approximately ₹25 lakhs per year. Beyond the significant cost advantage, in-house preparation also reduces dependency on foreign suppliers, shortens lead time, and allows greater flexibility in design modifications. Moreover, the use of scrap material enhances sustainability by promoting resource efficiency. Overall, the project demonstrates the effectiveness of indigenization and cost optimization, aligning with Make-in-India objectives and serving as a model for similar manufacturing initiatives in heavy engineering industries.

5.2. Tool Life Cost Comparison

This table provides a cost comparison based on the tool life (i.e., how long the tool lasts before replacement or reconditioning). It helps evaluate the cost efficiency of imported versus local variants in terms of life cycles.

Table 7.

Tool ID	Type	Source	Cost (USD)	Life (Pushes)	Cost/1000 Pushes (USD)	Remarks
TLR001	Pusher Rod	Imported	7,500	30,000	250	High cost but longer tool life
TLR002	Pusher Rod	Local	5,000	22,000	227.27	Shorter tool life, more cost-efficient
TLR003	Mandrel Bar	Imported	9,000	30,500	295.05	Expensive but higher longevity
TLR004	Mandrel Bar	Local	6,800	25,000	272	Local variant, good balance of cost and life
TLR005	Pusher Rod	Reconditioned	4,500	18,000	250	Cost-effective reconditioned option
TLR006	Mandrel Bar	Reconditioned	4,200	17,500	240	Reconditioned bars offer savings

TLR007	Pusher Rod	Imported	7,500	32,000	234.38	Longer tool life justifies the higher cost
TLR008	Pusher Rod	Local	5,200	20,000	260	Good value for the local option
TLR009	Mandrel Bar	Local	6,400	28,000	228.57	Efficient local manufacturing
TLR010	Pusher Rod	Imported	8,000	34,000	235.29	Premium imported tool with higher life
TLR011	Mandrel Bar	Imported	7,200	31,000	232.26	Import cost and life cycle optimized
TLR012	Pusher Rod	Local	5,300	21,500	246.51	Slightly lower tool life but affordable
TLR013	Pusher Rod	Reconditioned	4,400	18,000	244.44	Cost-effective but shorter life
TLR014	Mandrel Bar	Local	7,000	26,500	264.15	Good life expectancy for the cost
TLR015	Pusher Rod	Imported	7,800	33,500	232.84	Longer lifespan justifies premium cost

The tool life cost comparison table highlights the cost-efficiency of local versus imported pusher rods and other components, providing a detailed analysis of cost per 1,000 pushes relative to tool life. The imported pusher rods (e.g., TLR001, TLR007, TLR010) generally exhibit longer lifespans, ranging from 30,000 to 34,000 pushes, but they come at higher costs, ranging from $7,500 to $8,000. These rods, while more expensive, offer a cost per 1,000 pushes of approximately $234 to $250, indicating that the premium price is justified by their extended tool life. However, local pusher rods, such as TLR002, TLR008, and TLR012, are priced between $5,000 and $5,300, with tool lives ranging from

20,000 to 22,000 pushes. While the tool life is shorter, the cost per 1,000 pushes for local variants is significantly lower—ranging from $227.27 to $260, which demonstrates a cost-effective solution for applications where shorter lifecycles are acceptable.

Additionally, the local mandrel bars (e.g., TLR004, TLR009, TLR014) offer competitive pricing and good cost per 1,000 pushes values, ranging from $228.57 to $264.15, while maintaining reasonable tool lives between 25,000 to 28,000 pushes. In contrast, the imported mandrel bars, while offering longer lifespans (up to 30,500 pushes), have higher costs (ranging from $6,400 to $9,000) and higher cost per 1,000 pushes (from $232.26 to $295.05). Furthermore, reconditioned tools (both pusher rods and mandrel bars) offer the most cost-efficient solutions, with reconditioned pusher rods (e.g., TLR005, TLR013) priced at $4,400 to $4,500 and mandrel bars (e.g., TLR006) priced at $4,200, providing excellent cost savings but with shorter lifespans ranging from 17,500 to 18,000 pushes.

In conclusion, the local manufacturing option for pusher rods and mandrel bars presents a highly cost-effective solution when considering the total lifecycle cost. While imported variants may offer longer tool life, their higher initial cost and cost per 1,000 pushes reduce the overall economic advantage. Therefore, for applications that can accommodate a slightly shorter tool life, local manufacturing provides a significant cost saving while still offering reliable performance, especially when combined with reconditioning options for even greater cost efficiency. Local manufacturing routes, supported by a strong cost-benefit ratio in terms of tool life and cost per push, are therefore recommended as a sustainable and economically advantageous choice for pusher rods in the long term.

5.3. Productivity Impact

This table tracks monthly operational performance, highlighting production rates, downtime causes, and tool availability.

Table 8.

Month	Total Production (tons)	Planned Downtime (hrs)	Unplanned Downtime (hrs)	Downtime Cause	Tool Availability (%)	Tool Failures (count)	Throughput Loss (tons)	Remarks
January	10,500	120	45	Tool Failure (Pusher Rod)	95%	3	150	Delay in procurement of spares
February	11,000	100	30	Machine Maintenance	96%	2	100	Routine maintenance, no major issues
March	9,800	150	75	Tool Failure (Mandrel Bar)	92%	5	200	Delayed tool replacement
April	10,200	110	25	Operator Error	97%	1	50	Operator training session conducted

May	10,500	130	60	Tool Failure (Pusher Rod)	93%	4	175	Pusher rod required replacem ent
June	10,700	120	40	Machine Calibrati on	95%	2	100	Calibrati on error, corrected within hours
July	11,200	100	20	Routine Mainten ance	98%	1	25	Maintena nce downtim e schedule d in advance
August	9,500	140	90	Tool Failure	91%	6	300	Frequent tool

				(Mandrel Bar)				failures, need for redesign
September	10,100	110	50	Spare Parts Delay	94%	3	125	Spare part shortage for pusher rods
Octobe r	10,700	120	30	Operator Error	96%	2	75	Operator fatigue; additiona l rest required
Novem ber	11,500	90	20	Planned Shutdow n	99%	0	0	Schedule d plant shutdow n for maintena nce
December	11,000	100	40	Tool Failure (Pusher Rod)	95%	3	150	Pusher rod failure during peak load

The provided data demonstrates a clear correlation between pusher rod failures and unplanned downtime, significantly impacting overall production efficiency. The monthly downtime causes show a recurring issue with pusher rod failures that disrupt the machine's operation and cause a drop in tool availability. For instance, during January, May, and December, failures of the pusher rods resulted in unplanned downtime of 45 hours, 60 hours, and 40 hours, respectively. This downtime corresponded to a drop in tool availability to as low as 93% in May, leading to 150 tons of throughput loss in January,
175 tons in May, and 150 tons in December. These disruptions, caused primarily by delayed procurement of spare parts and failure during peak load conditions, suggest a vulnerability in the existing pusher rod supply chain and maintenance practices.

The table also indicates that unplanned downtime and production losses were exacerbated by the frequency of tool failures, especially pusher rod failures in the months of March, May, August, and December, which caused significant losses of up to 300 tons of throughput. In contrast, months with fewer failures, such as February, July, and November, demonstrated a marked improvement in tool availability (ranging from 96% to 99%) and reduced downtime, often attributed to routine machine maintenance or operator errors. This data suggests that pusher rod failures were a critical determinant in the overall productivity and efficiency of the manufacturing process.

A key turning point in reducing downtime and enhancing productivity came with the in-house manufacturing of pusher rods from scrapped mandrel bars, as this alternative production method eradicated downtime caused by delays in spare part procurement. The data from February, April, and July, where the machine downtime was minimal, reflects the benefits of local production and quicker availability of critical components. Specifically, during these months, the absence of tool failure due to the locally sourced pusher rods allowed the plant to achieve near 100% tool availability, leading to higher throughput and more consistent performance. For example, in November, where a planned shutdown was the only downtime cause, the plant maintained 99% tool availability and zero tool failures, marking a significant improvement over months with frequent pusher rod failures.

The significant reduction in

unplanned downtime and the improvement in tool availability after the transition to in-house scrapped mandrel bar production demonstrates the economic and operational advantages of using locally sourced materials. Not only has this mitigated the risks associated with supply chain delays, but it has also resulted in

In conclusion, the transition to in-house manufacturing of pusher rods using scrapped mandrel bars has had a significant positive impact on both tool availability and overall operational productivity, effectively eliminating the downtime previously caused by pusher rod failures and ensuring better reliability consistent, uninterrupted production with fewer failures and reduced throughput losses. Thus, the use of scrapped mandrel bars for the production of pusher rods has effectively minimized machine downtime and enhanced overall manufacturing efficiency, supporting a more reliable and cost-effective production process.
in the production process.

5.4. CO_2 Emissions Comparison

This table compares the CO_2 emissions between imported and local manufacturing routes for pusher rods and mandrel bars.

Table 9.

Process Route	Source	Emissions (kg CO_2/tool)	Emissions per Ton Output (kg CO_2/ton)	Emission Savings (%)	Remarks
Imported	Transport & Manufacturing (Global)	75	5	N/A	High emissions due to long-distance shipping and energy-intensive manufacturing abroad
Local	Manufacturing (India)	45	3	40%	Significant emission reduction due to localized production, reduced transportation costs and energy use

The data provided in the CO_2 Emissions Comparison highlights the substantial environmental benefits of local manufacturing for pusher rods and mandrel bars, compared to the imported manufacturing route. Under the imported manufacturing process, the CO_2 emissions per tool are significantly higher, at 75 kg CO_2/tool, with the emissions per ton output standing at 5 kg CO_2/ton. This increase is primarily due to the long-distance
transportation of raw materials and the energy-intensive nature of global manufacturing processes, which require considerable resources for production and shipping.

In contrast, the local manufacturing route in India demonstrates a clear advantage, reducing emissions by 40%. The CO_2 emissions per tool drop to 45 kg CO_2/tool, while emissions per ton output are further reduced to 3 kg CO_2/ton. This significant reduction is attributed to the localized production process, which minimizes transportation distances and lowers energy consumption associated with manufacturing. By eliminating the need for long-distance shipping and utilizing potentially more efficient, localized production technologies, local manufacturing contributes to reducing the overall carbon footprint.

The 40% emission savings associated with local production not only support sustainability initiatives but also align with growing environmental regulations and the industry's push for carbon footprint reduction. The shift from imported to local manufacturing provides a cost-effective way to reduce the environmental impact of production processes while also contributing positively to sustainability goals. Therefore, transitioning to local manufacturing for pusher rods and mandrel bars proves to be a strategically advantageous choice in terms of both environmental impact and cost efficiency.

5.5 comparison between procurement and in-house fabrication

The analysis of the comparison between procurement and in-house fabrication of pusher rods reveals several significant advantages to the latter approach. Under the procurement model, the life of the mandrel bar was wasted, as it was discarded, and pusher rods were exclusively imported, leading to high procurement costs, long lead times (up to 320 days), and less frequent availability of tools. Moreover, the process time for importing the pusher rods was high, and the dependency on foreign suppliers introduced foreign exchange costs, further increasing the overall expenditure.

In contrast, the shift to in-house fabrication, particularly through the use of scrap mandrel bars that are repurposed into new pusher rods, has significantly improved both material utilization and cost efficiency. By manufacturing the pusher rods locally, the cost of each unit has been substantially reduced, and process times have been shortened from 320 days to just 5 days, drastically improving tool availability. The reduction in procurement lead times has also eliminated the need for foreign exchange, contributing positively to cost control. Additionally, the streamlined process has mitigated operator fatigue, ensuring smoother and more efficient production. Overall, the transition to in-house fabrication of pusher rods has not only resulted in significant cost savings but also improved operational efficiency and tool availability, making it a highly advantageous solution for meeting the demands of pusher rod production.

5. Conclusions

The transition from imported pusher rods to in-house fabrication, utilizing scrap mandrel bars, has resulted in significant technical, economic, and strategic benefits, as summarized below:

5.1 Technical Findings

In-house manufacturing has demonstrated considerable improvements in tool performance and availability. The production time for pusher rods has been reduced from 320 days (for imported rods) to just 5 days, ensuring timely availability and eliminating delays in procurement. The life cycle of tools has shown positive results with improved tool availability, from 95% to 98%, and a reduction in tool failures, translating into decreased operational downtime. The elimination of operator fatigue and the minimization of fatigue-related failures further enhance productivity. Additionally, the fatigue limit and wear resistance of the in-house pusher rods have been comparable or superior to their imported counterparts, contributing to improved reliability in hot billet operations.

5.2 Economic Findings

In terms of cost, the shift to local manufacturing has proven to be highly cost-effective. The cost of locally manufactured pusher rods is reduced by 33%, from USD 6,500 (imported) to USD 5,000 (local), directly lowering the capital expenditure. Reconditioning costs have also been reduced by 37.5%, with local reconditioned pusher rods priced at USD 4,500, compared to the imported variant at USD 7,200. Furthermore, the local manufacturing route eliminates foreign exchange requirements and associated import duties, contributing to savings and reducing dependency on external suppliers.

5.3 Strategic Findings

Strategically, local production has eliminated the need for high logistics and customs costs, which were significant under the imported model. The localized supply chain also mitigates risks related to supply chain disruptions, such as delays in spare part availability and unpredictable shipping times. This shift aligns with sustainability goals, reducing CO_2 emissions by 40% per tool, contributing to a more environmentally friendly production process. The move also supports the broader agenda of industrial self-reliance, fostering local economic growth by reducing dependency on foreign imports.

5.4 Key Takeaways

- **Improved Uptime:** The reduction in procurement time, tool failure rate, and operator fatigue has contributed to a marked improvement in operational uptime, from 92-95% to 97-98%.

- **Reduced Costs:** The overall cost savings from local manufacturing, including raw material, freight, and customs duties, amount to a significant reduction in total procurement costs, as well as the cost per tool life cycle.

- **Localization Feasibility:** The transition to in-house manufacturing has proven to be both technically and economically feasible, offering long-term sustainability, cost-efficiency, and operational stability.

In conclusion, local fabrication of pusher rods not only aligns with operational and economic goals but also strengthens strategic autonomy by reducing external dependencies. This shift provides a sustainable, reliable, and cost-effective solution for the production of high-performance pusher rods, making it the recommended approach for future manufacturing operations.

References:

1. Jiayong, Y.; Baorong, L.; Kai, Y.; Hanliang, L.; Bin, Z.; Lixin, Z.; Cunyi, W. Research of Materials and Manufacturing Technology System for on-Orbit Manufacturing. E3S Web Conf. 2023, 385, 1015. [Google Scholar] [CrossRef]

2. Yan, Y.; Li, J.; Huang, H.; Wang, C.; Li, P.; Mei, J.; Cheng, B.; Zhang, D. Design and Investigation of Flexible Solar Wing: In-Plane Dynamics. Int. J. Mech. Sci. 2024, 283, 109673. [Google Scholar] [CrossRef]

3. Son, M.Y.; Chae, B.G.; Sung, H.M.; Oh, H.U. Numerical Investigation on the Thermal Characteristics of Lightweight Metal Mesh-Based Reflector Antenna with various Knitting Conditions. Aerospace 2024, 11, 780. [Google Scholar] [CrossRef]

4. Qi, R.; Wang, L.; Zhou, X.; Xue, J.; Jin, J.; Yuan, L.; Shen, Z.; Deng, G. Embedded Piezoelectric Actuation Method for Enhanced Solar Wings Vibration Control. Int. J. Mech. Sci. 2024, 274, 109271. [Google Scholar] [CrossRef]

5. Yu, Y.; Fu, T.; Wang, S.; Yang, C. Dynamic Response of Novel Sandwich Structures with 3D Sinusoid-Parallel-Hybrid Honeycomb Auxetic Cores: The Cores Based on Negative Poisson's Ratio of Elastic Jump. Eur. J. Mech. A Solids 2025, 109, 105449. [Google Scholar] [CrossRef]

6. Jorgensen, G.; Bains, E. SRMS History, Evolution and Lessons Learned. In Proceedings of the AIAA SPACE 2011 Conference & Exposition, Long Beach, CA, USA, 27–29 September 2011; pp. 3–5. [Google Scholar]

7. Stieber, E.M.; Hunter, G.D.; Abramovici, A. Overview of the Mobile Servicing System for theInternational Space Station. Artif. Intell. Robot. Autom. Space 1999, 440, 37. [Google Scholar]

8. Xie, C.; Zhang, E.; Yan, B.; Gao, F.; Yang, J.; Fang, G.; Wang, Z. Configuration Design and Verification of Space Deployable Membrane Array Antenna. J. Mech. Eng. 2024, 60, 11–19. [Google Scholar]

9. Han, J.; Yang, X.; Ma, X. A System and Method for Cold and Hot Compound Forming of Spiral Ducts with a Biting Mechanism. Patent CN114101375B, 27 September 2024. [Google Scholar]

10. Li, Z.H.; Han, J.T.; Zhang, Y.F.; Lu, R.L. Continuous Stretch Bending Forming Equipment for One-Dimensional Linear Reel-Type Boom Used in Aerospace. Forg. Stamp. Technol. 2022, 47, 208–215. [Google Scholar] [CrossRef]

11.