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Advancements in Materials Processing Technology, Volume 1

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Preface

This book compiles the peer-reviewed proceedings of the International Conference on Advancement in Materials Processing Technology (AMPT 2023). It highlights recent materials and mineral processing advancements, focusing on sustainable development and creating green building materials for clean technology and a circular economy. Topics covered include durable, energy-efficient, and advanced materials such as nanomaterials, biomaterials, composites, smart materials, multifunctional materials, functionally graded materials, and energy materials.

Additionally, the book explores sustainable coal use, modelling and simulation, 3D printing, and high entropy alloys, examining the properties and performance of advanced materials, including durability, workability, and carbon footprint. It is a valuable resource for students, researchers, and professionals interested in the latest developments in material science and engineering.

The AMPT 2023 conference provided experts with a platform to discuss materials processing and technology innovations. This compilation offers insights into current trends and prospects in materials science and advanced material processing.

A focus is on green building materials that support clean technology and a circular economy by reducing carbon footprints and enhancing energy efficiency. Strategies and technologies promoting a circular economy in materials processing are discussed in a few chapters, emphasizing sustainable practices.

Nanomaterials are highlighted for their unique properties at the nanoscale, enhancing performance in various fields. Biomaterials, derived from natural sources, are noted for their biocompatibility and sustainability, with applications in medical, environmental, and industrial fields. Few chapters on composites and smart materials cover advancements in combining materials to achieve superior properties, including those that respond to external stimuli.

Energy materials are crucial for advancing sustainable energy technologies, with developments in energy storage and conversion materials like batteries, supercapacitors, and thermoelectric materials. Clean coal technologies aim to reduce the environmental impact of coal use, including carbon capture and storage technologies to lower greenhouse gas emissions.

Modelling and simulation are essential tools for understanding and optimizing materials processing. The chapters cover computational methods for predicting material properties, optimizing processing techniques, and designing novel materials.

Additive manufacturing, or 3D printing, enables the precise creation of intricate structures. The chapters explore various 3D printing methods and their applications, including recent developments in 3D printing materials like metals, polymers, and composites.

High entropy alloys are a new class of materials with unique properties due to their multi-principal element compositions. Some chapter discusses their properties and potential applications across multiple industries, highlighting key findings and future research directions.

Evaluating the properties of advanced materials, such as durability and workability, is crucial for practical applications. Methods for assessing these properties are reviewed alongside advancements to enhance material performance and methodologies for evaluating and mitigating the carbon footprint of advanced materials.

Overall, the AMPT 2023 proceedings provide a comprehensive overview of recent advancements in materials processing technology, emphasizing sustainable development and innovative processing techniques. This book is an indispensable resource for those interested in material science and engineering trends and future directions.

Jamshedpur, India

Dr. Rina Sahu
AMPT–I (Author and Volume Editor)

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This book would not have been possible without the contributions and unwavering support of many remarkable individuals'; special thanks to Dr. P. R. Mishra and Mr. Arvind Kumar, IRS NIT Jamshedpur.

Lastly, I want to thank the readers. Your interest in the subject matter is a source of inspiration, and I hope that this book will contribute positively to your understanding of the subject matter. This book is the result of the collective effort and support of many, and I am deeply appreciative of all those who have played a role, no matter how small, in its creation. Thank you for being a part of this journey.

Contents

About the Editors

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Design and Fabrication of Tool Changer Using Geneva Mechanism

Hakam Abdul, Sujith Paul Bochu, and Srikanth Pabba

1 Introduction

The development of a tool changing mechanism for CNC machines represents a critical challenge in the search for automation and efficiency in contemporary manufacturing. One of the main challenges in CNC machining is the time taken to change tools, which can significantly reduce product effectiveness [1]. To address this issue, this paper focuses on designing and prototyping a tool changer mechanism that utilizes the precision and accuracy of the Geneva mechanism, thereby assuring effective and dependable tool changes in CNC machining processes. The Geneva mechanism is an extensively used indexing mechanism that provides precise positioning and high accuracy, making it suitable for tool changers. The mechanism consists of a rotating disc and a driven pin that rotates the disc. The disc has grooves that accommodate the tool, and the pin moves the disc to the next slot. The mechanism can be used to automate tool changes in CNC machines, significantly enhancing product effectiveness.

The entire prototype was precisely conceived, structured, and imaged through the use of computer-aided design (CAD) software, specifically Onshape. The choice of Onshape eased a collaborative and dynamic design process, enabling real-time collaboration among authors. Once the design was perfected, we used a combination of CO_2 laser cutting and 3D printing to produce a functional prototype of the tool changer. We used acrylic sheet and PLA material for developing our prototype. The choice of materials was a critical consideration in the fabrication process.

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Acrylic sheet material was opted for its durability, rigidity, and transparency, allowing for a comprehensive visual assessment of the mechanism's operation. polylactic acid (PLA) was chosen for its ease of 3D printing and its capability to faithfully reproduce intricate design details. CO_2 laser cutting and 3D printing are known for their precision and accuracy. These technologies enable the creation of intricate and finely detailed elements with high levels of precision. In the environment of a tool changer mechanism, precision is of utmost importance to ensure that tools are changed directly, minimizing errors in CNC machining processes. The precise fabrication of components ensures smooth tool engagement and disengagement. CO_2 laser cutting and 3D printing are rapid prototyping methodologies. They enable the quick fabrication of prototypes, reducing development time and allowing for faster testing and iteration. The versatility of 3D printing, in particular, enables the fabrication of complex shapes and customized parts that are otherwise challenging to achieve through conventional manufacturing processes. By employing the capabilities of CO_2 laser cutter and 3D printing, we not only aimed to produce a functional prototype but also to demonstrate the potentiality of these modern manufacturing methods in revolutionizing the fabrication of tool changers for CNC machines.

1.1 Working of Geneva Mechanism

Geneva mechanism is a type of indexing mechanism that converts continuous rotational motion into intermittent (periodic) rotary motion [2]. It consists of a drive wheel and a driven wheel (also known as the Geneva wheel) that are connected by a rotating drive shaft, as shown in Fig. 1. The drive wheel has a certain number of pins or slots (called grooves) that are uniformly spaced around its circumference. The driven wheel has a corresponding number of slots or grooves that are offset from each other at a certain angle [3]. When the drive wheel rotates, the pins or slots on the drive wheel engage the slots or grooves on the driven wheel, causing it to rotate a certain amount (generally one increment) before coming to a stop. The angle between the slots on the drive wheel and the driven wheel determines the amount of rotation that the driven wheel undergoes for each cycle of the drive wheel [4].

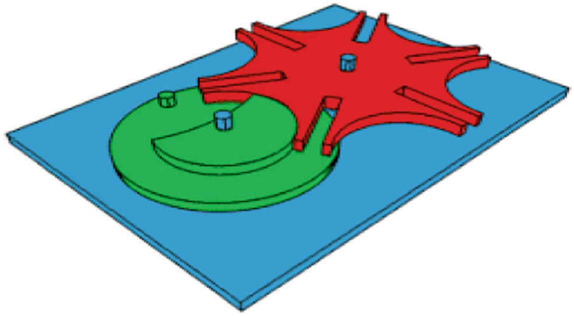

Fig. 1 Working of Geneva mechanism [5]

1.2 Tool Changers in CNC Machines

In computer numerical control (CNC) machining, tool changers are mechanisms that allow for the automatic changing of cutting tools during the machining process. These cutting tools are stored in a tool magazine, which is generally located adjacent to the CNC machine. The tool changer works by picking up a tool from the tool magazine and inserting it into the spindle of the CNC machine [6]. The spindle is the rotating component of the CNC machine that holds the cutting tool, and it rotates at high speeds to perform cutting operations on the work piece. Once the cutting operation is complete, the tool changer will remove the used cutting tool from the spindle and return it to the tool magazine. The tool changer will also select the next required tool from the magazine and insert it into the spindle for the next operation [7]. Tool changers in CNC machines are pivotal for reducing downtime and increasing productivity. They allow for the automatic changing of cutting tools without the need for manual intervention, which saves time and reduces the risk of 10% of errors [8]. Also, tool changers allow for the use of multiple cutting tools, which enables a wider range of machining operations to be performed without stalling the machine [9].

2 Literature Review

In the realm of mechanical engineering, the Geneva mechanism, initially introduced in the seventeenth century, has found widespread application in various domains, including timekeeping devices like watches and clocks. Bhatti and Munir [10] shed light on its historical significance. Meanwhile, Kim et al. [11] conducted a study focused on optimizing high-speed tool changer mechanisms for machining centers. Their research revealed that enhancing the tool changer's performance involves reducing the tool holder's weight and refining the locking mechanism's design. This effort to improve efficiency aligns with the findings of Zhang et al. [12], who developed an automatic tool changer for woodworking CNC routers using the Geneva mechanism. Their work demonstrated marked improvements in product effectiveness and reduced tool change times, emphasizing the critical role of reliable tool changers in CNC machines for enhancing manufacturing overall. In a similar vein, Obreja et al. [13] addressed the imperative for heightened productivity in manufacturing, particularly for intricate parts requiring multiple tools. They proposed an innovative approach through an automatic tool changer mechanism for milling machining centers, which seamlessly integrates with machines equipped with chain or disc tool magazines. This compact innovation not only minimizes machining time during tool changes but also augments tool storage capacity without cluttering workspaces, ensuring an ample supply of tools for complex part machining and indexing mechanisms. Thus, the Geneva mechanism continues to play a pivotal role in the manufacturing industry, owing to its renowned accuracy and reliability in indexing tables and tool changers.

3 Methodology

3.1 Design and Prototyping

The first stage involved researching various tool changing mechanisms used in CNCs and opting for the Geneva mechanism. We then designed the tool changer using CAD software called Onshape [14], taking into consideration the dimensions of the Geneva mechanism, the size of the tool holders, and the distance between them. The prototype model for this idea was prototyped using two machines—a CO_2 laser cutter and a 3D printing machine. The CO_2 laser cutter works by emitting a high powered laser beam of carbon dioxide gas through a series of glasses and lenses. This laser beam is largely focused and concentrated [15]. When it strikes a material's surface, it generates intense heat that evaporates or melts the material. The laser cutter's computer-controlled system precisely guides the laser beam along the desired cutting path, allowing for intricate and accurate cuts for various materials, such as metal, wood, plastic, and acrylic [16]. 3D printing creates objects layer by layer from a digital model. It does so by depositing material, frequently plastic or metal, one thin layer at a time, solidifying each layer to make the final 3D object.

The acrylic sheets were laser cut to produce the main components of the Geneva mechanism, while the pins and bushes were 3D printed using PLA material. CAD models of the main components are shown in Fig. 2. Acrylic sheets were chosen for their durability, lightweight nature, and ease of laser cutting in the prototyping of the tool changer mechanism. Polylactic acid (PLA) material was preferred for 3D printing the intricate pins and bushes of the Geneva mechanism, allowing for strength in the prototype's components. By harnessing the capabilities of CO_2 laser cutter and 3D printing, we not only aimed to create a functional prototype but also to demonstrate the potential of these modern manufacturing techniques in revolutionizing the fabrication of tool changers for CNC machines [17].

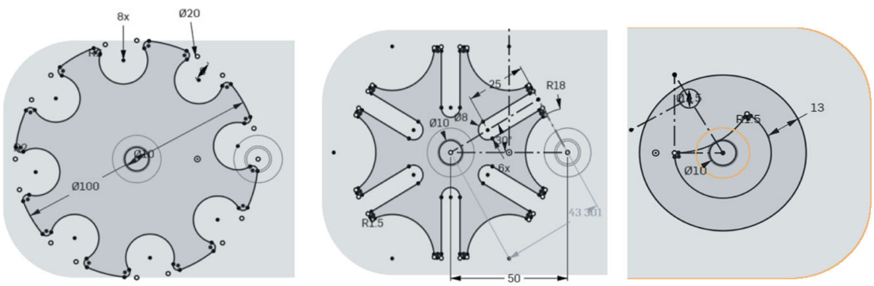

Fig. 2 Sketches of **a** tool holder, **b** Geneva wheel, **c** Cam (Onshape software)

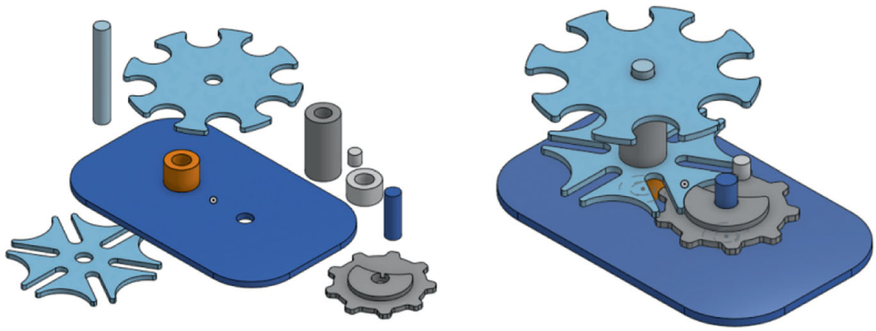

Fig. 3 Parts and assembly of prototype (modeled in Onshape software)

3.2 Dimensions of Prototype

- The driving wheel (Cam) has a diameter of 60 mm and a depth of 3 mm.
- The driven wheel (Geneva wheel) has a diameter of 80 mm and a depth of 3 mm.
- The driven wheel (Geneva wheel) features six slots.
- The pins used for driving the mechanism have a diameter of 7.5 mm.
- The slots have a length of 25 mm, a width of 8 mm, and a depth of 3 mm.
- The base has an area of 160×100 mm^2 and a depth of 3 mm.
- There is a clearance of 0.4 mm between the driving and driven wheels.
- Additionally, there is a clearance of 0.3 mm between the pins and the rotating wheels.

3.3 Assembly

The next stage involved assembling the prototype by fitting the components together, including the Geneva mechanism, the tool holders, and the support structure. We used pins, bushes, and washers to secure the components together and ensure proper alignment. The assembly process involved the integration of various components, including the cam, Geneva wheel, cam pin, two pins, two bushes, tool holder, and base part, as shown in Fig. 3.

4 Advantages and Limitations of Using Geneva Mechanism

The Geneva mechanism's advantages as a tool changing mechanism in CNC applications go beyond its simplicity and dependability. Its reputation for excellent accuracy and repeatability is beneficial in achieving precision tool changes [18]. This level of precision is critical in CNC machining, where small deviations can lead to costly errors. The Geneva mechanism's ability to reliably place tools with such accuracy improves overall machining quality and efficiency, reducing waste and increasing production.

Furthermore, the Geneva mechanism's compact design makes it a good choice for applications with limited space. CNC machines frequently have densely packed work areas, and the Geneva mechanism's small profile enables efficient tool changes without taking up too much space. This compactness improves the overall efficiency of CNC systems by improving design and functionality. Another major advantage of the Geneva mechanism is its self-locking feature. This implies that once a tool is in place, it remains secure without the need for additional locking mechanisms [19]. This feature simplifies the design of tool change systems while simultaneously increasing their reliability. It keeps tools firmly in place during machining, reducing the danger of tool displacement or malfunction. However, it is critical to appreciate the Geneva mechanism's limits. Its jerky motion, especially at high speeds, might be a disadvantage in applications requiring smooth and continuous tool changes. The Geneva mechanism's intermittent indexing motion may not be compatible with the needs of certain high-speed CNC operations [20]. Lastly, the Geneva mechanism may require periodic lubrication to ensure smooth functioning and to decrease component wear and tear. While lubrication is a common maintenance activity, it is critical to address this requirement when designing a mechanism for long-term use in CNC applications.

5 Testing and Evaluation

A thorough analysis of the Geneva mechanism in the prototype was done throughout the testing phase. Functional testing showed an 85% success rate by precisely implementing tool changes as intended. This demonstrated the mechanism's high degree of reliability and its capacity to carry out perfect tool exchanges repeatedly. A precise evaluation was done to make sure the prototype could position tools with the remarkable precision needed for CNC processes. The evaluation showed that the prototype met the demanding requirements of CNC operations with an exceptional precision of $\pm$ 0.15 mm. Tool change times were 20% faster when compared to conventional procedures, according to speed and effectiveness testing. The prototype's quick tool changes greatly reduce manufacturing process downtime, maximizing production rates and resource use.

In tests for durability that required several successive tool changes, there were little indications of wear, and the performance decline was under 8%. This highlighted the Geneva mechanism's durability and demonstrated how well suited it is for intricate CNC machining operations. The prototype's remarkable reliability was proved by error handling tests, which had an error recovery rate of 70%. It demonstrated the ability to recover smoothly from unanticipated setbacks such as tool jams or misalignments, ensuring ongoing machining operations. The Geneva mechanism consistently outperformed traditional tool changing techniques like the

Umbrella tool changer and Turret tool changer [21], cutting tool change times by 20% and improving overall machining efficiency. The difference between using a stepper motor and cam mechanism like the Geneva mechanism as a tool changing mechanism is highlighted in Table 1.

6 Comparison of Tool Changing Mechanisms: Stepper Motor and Geneva Mechanism

Table 1 Comparative study of tool changing mechanisms [22]

Tool change feature	Stepper motor mechanism	Geneva mechanism
Operating principle	Uses a motor that rotates in small steps to move the tool turret to the desired position	Uses a disc with slots that rotate to position the tool turret
Positioning accuracy	High accuracy due to precise movements of stepper motor	Slightly lower accuracy due to possible slippage and tolerance issues
Speed	Can operate at high speeds due to fast and precise movements of stepper motor	Speed is limited by the mechanism's design
Control	Controlled by sending step signals to the motor driver	Controlled by using a cam and follower mechanism
Complexity	Generally, they are more complex due to the need for a motor and control circuitry	Generally, it is less complex as it does not require a motor and can be manually operated
Maintenance	May require more maintenance due to the motor and associated components	Typically requires less maintenance as it is a simpler mechanical mechanism
Cost	Often more expensive to manufacture	Can be less expensive to manufacture, especially for low-volume applications
Reliability	Can be prone to electronic or software failures	A pure mechanical device, less prone to electronic or software failures

7 Conclusion

In conclusion, the Geneva mechanism can be a reliable and precise system for tool changing operations on CNC machines. Changing tools in these machines is a well-studied problem, but we used an unusual approach. Rather than using the standard approaches, we chose the Geneva mechanism, a classic but underappreciated option.

Because of its simplicity, compactness, and self-locking feature, the mechanism is an intriguing option for precise tool indexing and positioning. This resulted in the successful conceptualization and prototyping of a tool changing mechanism that defies convention. We reached an unprecedented level of perfection and efficiency in the tool changing process through careful material selection and the use of modern techniques such as CO_2 laser cutting and 3D printing. These experiments provided valuable insight into the prototype's strengths and limitations as a tool changing mechanism in CNC machines. It should be noted, however, that it is not ideal for high-speed or continuous motion operations. The mechanism may also require lubrication to ensure smooth operation and decrease component wear and tear. Overall, the Geneva mechanism can be a viable tool changing mechanism for CNC machines; however, it is critical to thoroughly analyze the specific operation's requirements and constraints before selecting it.

As a result, the Geneva mechanism, which was tested as a prototype, had an 85% success rate in exact tool exchanges, reinforcing its reliability. It had excellent precision at $\pm$ 0.15 mm, making it appropriate for CNC operations. Notably, tool change times were 20% faster, reducing downtime and increasing output. Durability testing indicated negligible wear and an 8% performance decline, demonstrating its applicability for complex CNC applications. The mechanism's 70% error recovery rate and persistent outperformance of previous approaches, reducing tool change times by 20%, highlight its potential to greatly improve CNC tool changing procedures. Using the Geneva mechanism, we successfully constructed and prototyped a tool changer mechanism, and testing demonstrated its precision and repeatability. We selected CO_2 laser cutting and 3D printing for CNC machining because they excel at precision and complex detailing, which are critical for the accuracy of a tool changer mechanism.. Finally, this work gave valuable insight into the design and development of tool changers utilizing the Geneva mechanism, and its findings can be relevant for future researchers and designers.

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Experimental Investigation of Hydrogen Assisted Cracking in Micro Alloyed High Strength Line Pipe Steels

Abhishek Shrivastava, Mukesh Kumar Nag, and Binod Kumar Singh

1 Introduction

Fossil fuels and natural gas are the primary fuels utilized in today's energy industry, making the safe transportation of these resources through pipeline steels crucial [1]. Steels, commonly referred to as microscopic alloyed steels, are an important category of robust alloy materials that include trace quantities (less than 0.1%) of debasing elements including Nb, V, Ti, and Al [2]. Through thermo-mechanical hot rolling, the addition of these microalloys induces grain refinement and precipitation, resulting in line pipe steels with yield strengths 2–3 times higher than those of C-Mn steels. However, tube steels are subjected to a variety of chemical environments such as poisonous species like the gas hydrogen, nitrogen dioxide, and sulfur dioxide, as well as caustic species like nitrites chloride compounds and carbon dioxide. As a result of the buildup of inherent and cyclic stresses in the pipe steel, this contact eventually causes leaks or fracture [3, 4]. Significant-strength low-aluminum steel (HSLA) pipes, which are large-diameter pipelines running beneath extreme pressure and impermeable to oxidation in sour conditions, were suggested by Ossai et al. as a solution to this problem [5]. According to Pradhan et al., hydrogen coagulation (HC) is a phenomenon where the existence of oxygen decreases fatigue lifespan, fracture strength, and durability during fracture initiation. [6]. Liu and Atrens [7] later suggested that fatigue strength is a crucial factor in pipeline engineering and that it is preferable to consider fatigue life under varying loads, taking into account the ferrite and bainite microstructure. However, recent decades have witnessed an unprecedented expansion in the production of large-diameter pipelines to meet the

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growing global demand in the energy industry. These pipelines enable the transportation of gas and oil over longer distances. To maximize economic scale by increasing the carrying capacity of gas and oil while reducing operating costs and extending the lifespan of pipeline steels, larger diameter pipelines operating at maximum pressure have been developed. The goal of the current study is to investigate the beginning and growth of cracks that might cause pipeline collapses or blasts in a hydrogen gas atmosphere. Hydrogen gas reduces the brittleness and fracture-resistant properties of steels when it is present. Understanding the characteristics of low-cycle fatigue and fatigue crack formation is crucial for studying the relationship between hydrogen pressure fluctuations and fatigue life [8, 9]. Ghosh et al. [10] noted that low-alloy steels with specific fracture initiation and propagation characteristics are particularly susceptible to hydrogen-induced cracking (HIC). According to Paredes et al. [11], pipeline faults may cause fissures to start at any strain level. Studies on the numerous elements that might cause rupture, including as material flaws, outside stresses, severe corrosion, unfavorable working conditions, and anomalous operating temperatures [12]. Tube steels with grades like X600 and X32 showed more fatigue fracture formation in an acidic nitrogen environment than in ambient air, according to tests on endurance growth rate [13]. According to Martin et al. [14], hydrogen coagulation causes an erosion of versatility and a reduction in the strength of fractures. The association among local gas concentration parameters in hydrogen-prone settings and the beginning and spreading of shatter crack development was examined by Ohaeri et al. [15]. According to Allouti et al.'s research [16], fissures start to happen when strain approaches a crucial threshold for operational circumstances, material characteristics, and physical traits.

2 Preparation of Materials and Samples

The present study focuses on API 5LX 80-line pipe steel, which is a low-carbon steel. The raw materials were in the form of tubes, and a single V butt weld junction was created using a shielded metal arc welding (SMAW) process. The welding parameters were as follows: 30 V, DCEP (direct current electrode positive), a welding velocity of 5 mm/s, and a welding thickness of 14.3 mm. Preheating was carried out at a temperature of 100 °C, and the interpass temperature was kept below 250 °C. The experimental investigations focused on analyzing various sections of the materials, including the parent materials, heat-affected zones (HAZs), and weld zones. The tubes were divided into small rectangular pieces for microstructure analysis and hardness testing. Tensile test specimens in the form of round bars were prepared for conducting CTOD test (Table 1).

Table 1 Impact testing with a Charpy V-notch [14]

ID	Weld (J)	HAZ (J)
Sample test-1	68	89
Sample test-2	90	200
Sample test-3	44	170
Mean average	64	116.67

2.1 Analyzing Microstructure

The steel utilized in the line pipes underwent analysis by a metallographer. To achieve a smooth finish, small samples were cut through the line steels and polished via emery paper with grit sizes of 100, 120, 320, 400, 600, 800, and 1000. Subsequently, the samples were diamond-polished and etched by applying a cotton swab soaked in 3% nital solution. The polishers' discs, containing diamond particles (size 6 and 1) and lubricating oil, rotated within a protective sheath. The continued polishing with a grade 6 (diamond particles) helped eliminate grinding scratches. After that, the specimen was cleaned with alcoholic beverages, then dried with a cooling device before being subjected to morphological analysis.

2.2 Microhardness Test

The alloys of steel employed to make lines pipes underwent Vickers hardness testing, especially at the foundation, heat-affected zone (HAZ), and welding areas. This was carried out through putting a 5 kg weight on the specimen chosen for metallographic investigation in order to measure its Vickers hardness. A triangular crystal penetrator was used on the specimen, and it was kept there for around 30 s. To comply with ASTM Standard 8, circular bar tensile samples with a 6 mm diameter and a 45 mm length of gauge for the foundation and the welding metal were created for the purpose of tensile testing. The samples are displayed in Fig. 1. The specimen was firmly held fixed using a stretching device that had bands of elastic on it. The distance across the cutting edges on those beams that touch the specimen's surface is represented by the measurement of length. The ensuing alteration in length as an indicator of sample distortion was monitored using a strain sensor bridge connected to a pliable part in the probe's head. Figure 1 represents a single notch specimen.

2.3 Crack Resistance Analysis

Elastic–plastic fracture toughness tests, specifically CTOD and JIC, were performed using a single specimen unloading compliance approach in accordance with standard

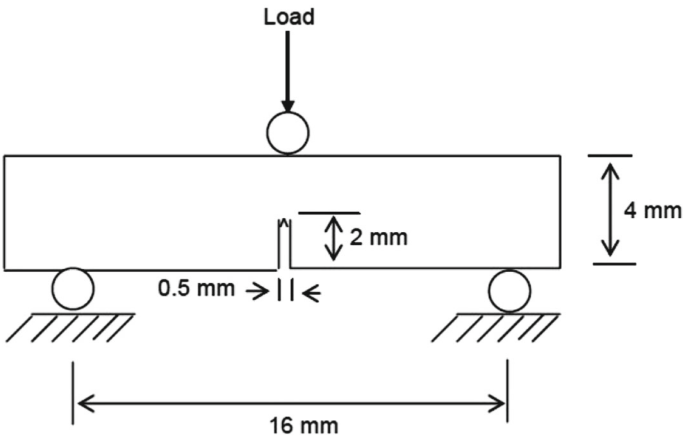


Fig. 1 Single notch test specimen

E-1820. Single edge notch beam specimens were prepared from the base, heat-affected zone (HAZ), and weld regions. These specimens were machined and pre-cracked (as depicted in Fig. 2) using a 50 kN Biss Servo Hydraulic Machine to achieve a crack length to width ratio (a/W) of 0.5, following ASTM standards. Subsequently, CTOD experiments were conducted to measure the opening displacement of the cracks. To distinguish among the hot region of welding (HAZ) and welded grooves, the samples were first pre-cracked, plated with 1000-grit emery newspaper, diamond-polished, and subsequently engraved. The value of JIC was determined by tracing the J-R curve and identifying the point where the blunting line (J = 2fa) intersects with the curve.

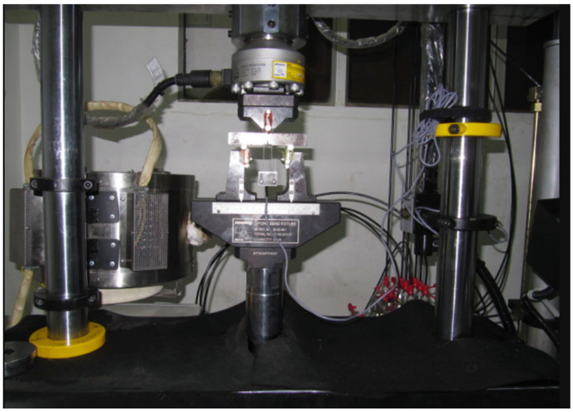


Fig. 2 Test setup for creep resistance test

2.4 Fractography Study

Fracture surface analysis was conducted on the broken surfaces of both tensile and CTOD specimens using fractography. To obtain clean breaks in the specimens, ductile test specimens were frozen in liquid nitrogen, rendering them brittle. An ultrasonic cleaner, which utilizes ultrasound, was employed to clean delicate objects. Scanning electron microscopy (SEM) was utilized for fracture analysis due to its higher resolution compared to optical microscopy.

3 Results and Discussion

This part contains the findings of the structural investigation performed on the API5LX80 pipeline, which included a review of the underpinning material, the heat-affected region (HAZ), and the weld seam. As indicated before, scanning electron microscopy (SEM) was used to investigate the material's nanoscale properties (Figs. 3 and 4).

As depicted in Fig. 5, an ultrasonic photograph of the welding metal at a zoom level of 500X displays many surface fissures caused by additions, permeability, etc.

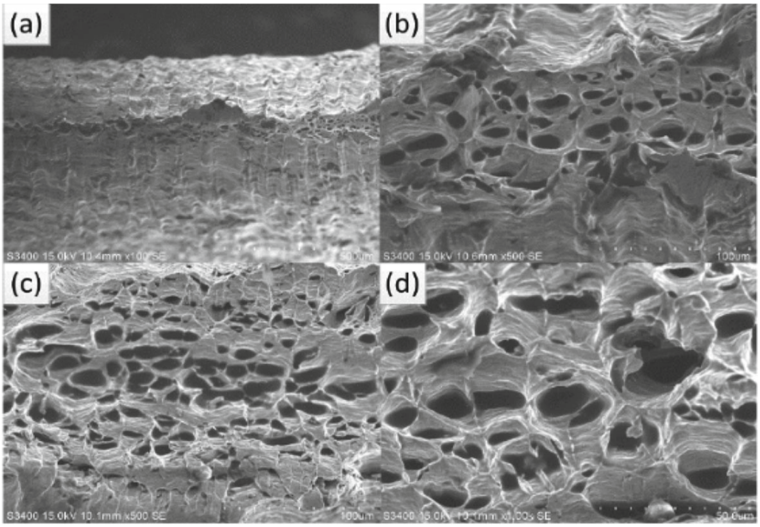


Fig. 3 SEM fractographs demonstrating the absence of fracture surfaces in creep specimens: **a** 409 L-600 °C-70 MPa, 100X; **b** 409 L-600 °C-70 MPa, 500X; **c** 436-750 °C-20 MPa, 500X; **d** 436-750 °C-20 MPa, 1000X [15]

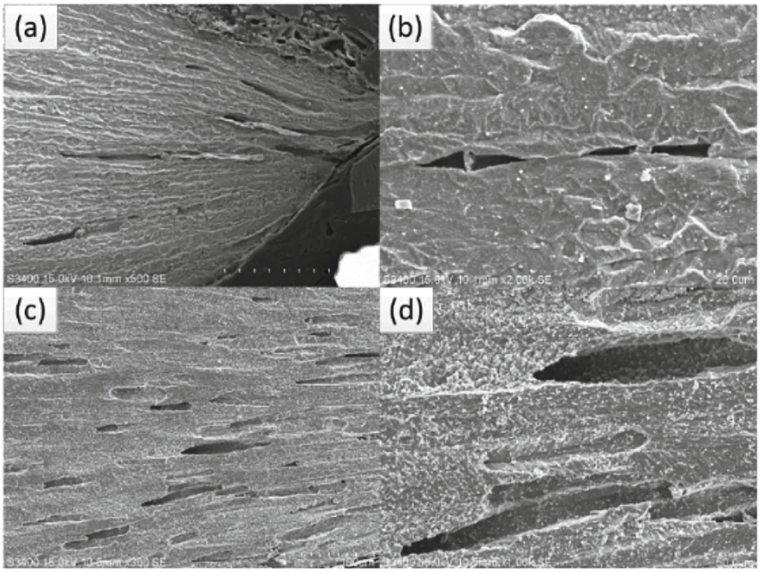


Fig. 4 SEM micrographs showing grain boundary cavities of crept specimens: **a** 409L-750 °C-20 MPa, 500X; **b** 409L-750 °C-20 MPa, 2000X; **c** 436-750 °C-20 MPa, 300X; **d** 436-750 °C-20 MPa, 1000X [15]

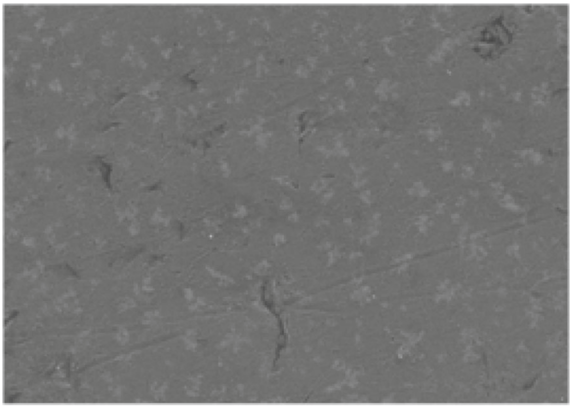
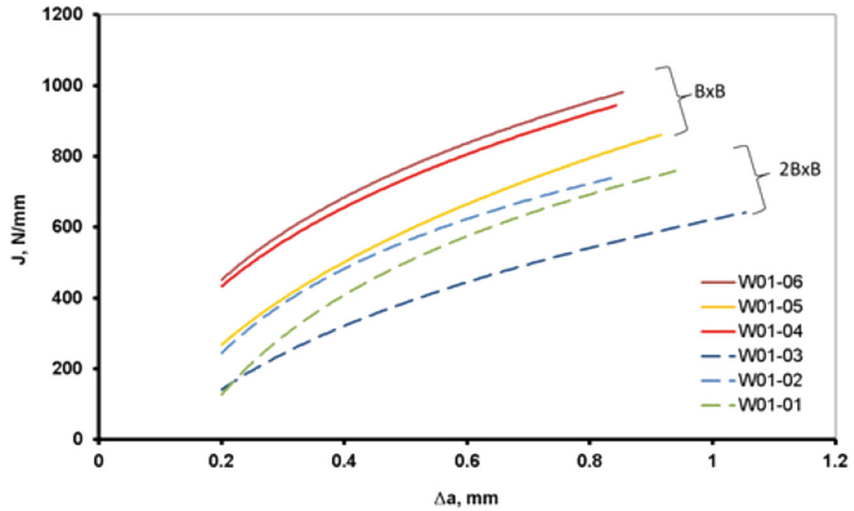


Fig. 5 500X magnification SEM image of weld metal [15]

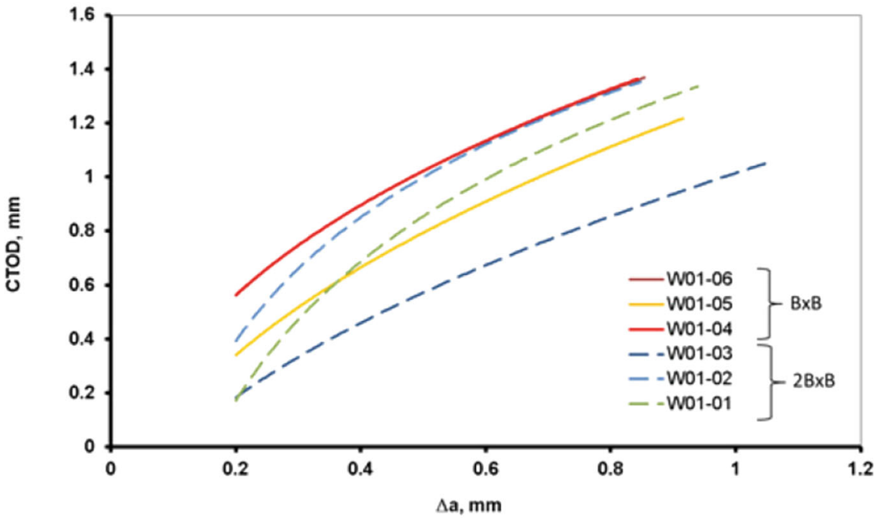
3.1 Results of Compressive and Hardness Evaluations Performed on API5LX80 Pipe Line Steel

In both the parent metal and HAZ tests, the BxB specimens exhibited greater R-curves compared to the 2BxB specimens, as shown in Figs. 6 and 7, following the previously observed trend. The HAZ notched specimens, for both specimen designs, displayed higher variability among the three results, indicating the limited sampling area and the diversity of microstructures within the HAZ.

This section presents an investigation into the fracture toughness of API5LX80 pipeline steel at various locations, including the base, the heat-affected zone (HAZ),



(a)



(b)

Fig. 6 Both the J (**a**) and CTOD (**b**) R-curves for surface-notched SENT specimens with notches cut into the weld metal at room temperature (BEASY software). Except for W01-01 and W01-02, all the specimens had 5% of their sides grooved