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Survey of Mechanical Property Enhancement Techniques for Piping Materials

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***Abstract*—Failure of pipelines may pose significant hazards leading to detrimental environmental and economic impacts. Since the beginning of this millennium, nearly 600 severe gas pipe incidents were reported with more than 200 fatalities. This paper provides an exhaustive state of art analysis of piping materials, metallurgical enhancement methods, and surface engineering methods and how they are applied to pipeline and mechanical systems in the modern world. Both metallic and non-metallic piping materials are discussed, with emphasis put on their mechanical properties, corrosion, manufacturability, and ability to work in various service environments. Some of the key metallic materials include carbon steels, alloy steels, stainless steels and non-ferrous alloys are discussed together with non-metallic alternatives like polymers and fiber-reinforced composite materials highlighting their pros, cons and their use in industry. The paper also discusses the key mechanical properties that control the performance of pipes, including yield strength, tensile strength, ductility and toughness. Heat treatment, thermomechanical processing and severe plastic deformation are the methods of advanced metallurgical enhancement that are analyzed in terms of microstructure and mechanical performance enhancement. Also, surface engineering techniques, including, but not limited to, coating technologies, surface modification and thermal treatments are considered in terms of their effectiveness to increase wear resistance, corrosion protection and service life.**

Keywords—Pipeline Safety, Piping Materials, Metallic and Non-Metallic Pipes, Mechanical Properties, Corrosion Resistance, Heat Treatment, Pipeline Durability.

I. INTRODUCTION

System of piping is thousands of years old and has played a crucial role in the functioning of the society and regarded as the most essential infrastructure in the modern world. They are defined as a set of tubes and their accessories are used to transport liquids, gases, and suspended solids [1]. Piping systems are required by every industry and their significance is more especially in process industries where they constitute an average of 20 to 25% of the installation costs [2], 45 to 50% of the equipment assembly costs and 20% of the entire project cost. This reliability tendency reduces with the life span of pipelines as seen in the reduced downtime and accidents. Piping systems should have lifespans exceeding over 15 years [3], to maximize the profitability of the process, and this usually goes beyond this period in developed nations. For instance, in Calgary (Canada), a significant portion of the sewage infrastructure is old: 5.24% of the pipes are over 65 years old, and 3.4% have been in place for more than 100 years. People are now moving towards not only developing more durable systems, but also prolonging the life of already existing systems, casting doubts on the safety and reliability of old pipelines.

Pipeline steels for transportation of oil and gas have been under development for several decades [4]. The micro-alloyed pipeline steel is still a research hotspot due to the increasing pipeline construction around the world. With the rapid economic development and the continuous depletion of oil and gas resources, such hostile conditions as high-pressure in deep water, extremely low temperature, as well as corrosion environments have become common in the oil and gas exploitation. This gives rise to a demand for high quality special pipeline steels to make pipes with good resistance to the poor environment during the exploitation and transportation.

A simple and prompt method to determine the mechanical properties of industrial multilayer extrusion polypropylene pipes for a gravity sewer network is suggested. The engineering formulas included for calculating the permissible thickness and relative position of a foam core in the pipes are based on a linear-elastic approximation and the rule of mixtures [5]. The protection of connections and cables is an essential element in various applications, e.g., industrial machines, robots, rail vehicles, cars, cranes, aviation, electronics, and electrical engineering. The products used for this protection have to be simple in design and assembly and reliable in operation. Cellular structure Thermoplastic foams are prepared by an expanding blowing agent (typically a gaseous phase) dispersed in the polymer melt. Due to their increased stiffness-to-weight ratios, the foams reduce the amount of PP used and, accordingly, diminish the cost of finished products.

An alternative to cut and weld concept is the use of Mechanical [6] Pipe Connections that are being designed to join and part various cooling and purge pipes during blanket maintenance. As mechanical [6] pipe connections have been used and standardized, whether in flange connection form or in clamped, all the mechanical pipe connections available are of single-pipe connection type [7]. To be deployed in DEMO, the manifold design with several pipes attached to the identical flange is designed to minimize the downtime and increase the speed of maintenance. Up to now, the mechanical behavior of lined pipe systems under various loading conditions has been extensively studied in recent years.

A. Structure of the Paper

This paper is organized as follows:

II. Piping Materials: State of The Art

Pipe material is defined as the types of materials used in building pipes, which have developed with time to be of wood, clay, metal (copper, lead and cast iron), steel as well as the latest materials, plastic and composite material. All kinds of pipe material have their own characteristics, benefits, and drawbacks that determine the use of this material in various industries like water distribution systems, sewage systems, and other engineering systems. An important decision to be made when planning the installation of a new pipeline or modifications to an existing pipeline is to determine the materials to be used in the design and construction of the line.

A. Metallic Piping Materials

Metallic pipelines carrying water and/or oil/gas are exposed to deterioration, leaks/bursts, and failures due to corrosion. A suitable corrosion protection technique can prevent corrosion of these metallic pipelines [8], particularly in hostile environments, and corrosive soils. It can also reduce pipe deterioration, leaks/breaks, and failure, prolong service life, and improve the transportation process.

1) Carbon Steels

Low, medium, and high carbon steels are commonly used as structural materials because of their balanced skewed mechanical characteristics and high economy. The need to learn and solve the metallurgical and mechanical [9] problems that accompany the welding process is illustrated by the demand of carbon steel structure that is needed across the world. An example [10] is ASTM A516 Grade 70 which is known to have high yield strength, toughness as well as resistance to brittle fractures which is widely used in the production of pressure vessels [11], boilers and storage tanks particularly in low temperature environment.

2) Alloy Steels

To ensure high-strength and corrosion-resistant properties of steel, a sufficiently large percentage of alloying elements, such as chromium, nickel, molybdenum and etc. are added into steel. However, these elements usually impair steel plastic properties in the process of pipe manufacturing by pressure treatment [12]. Consequently, cracks and breaks may occur on hot-worked pipes. Therefore, the process of pipe manufacture engineering requires reliable information concerning ductility of steels used for pipe production.

3) Stainless Steel

A set of stainless-steel tabular heat pipes are successfully fabricated, for the purpose of the low-grade heat recovery applications in a corrosion exhaust environment. Heat pipes are generally made of copper, however it is weak in corrosion resistance point of view. In the study, therefore, a set of heat pipes are fabricated of stainless steels [13]. It is expected that the heat transfer performance of stainless steel heat pipes should be lowered compared to copper one, because the thermal conductivity of stainless steel is much lower than that of copper.

4) Non-ferrous Alloys

With the development of modern technology, the growing demand for advanced non-ferrous alloys (Aluminium, Copper, Nickel, Lead and Zinc, etc.) drives the development of the non-ferrous metallurgy industry. Moreover, non-ferrous alloys play a key role in many high-tech fields and promote the development and progress of industrial countries. Advanced non-ferrous alloys with excellent properties (high strength, excellent ductility, good wear resistance and corrosion resistance, etc.) are also widely used in various fields, such as automobiles, electronics, aviation, aerospace and biomedicine.

B. Non-Metallic Piping Materials

Non-metallic pipelines are gaining popularity across the Oil and Gas [14] value chain from upstream to downstream applications. Among the top benefits are mitigation of corrosion hazards, lowering the total cost of ownership, and reducing carbon footprint [15]. Whereas non-metallic pipes are used increasingly at both onshore and offshore areas, attention should be drawn on downhole tubular development and qualification since they are not adequately discussed in literature.

1) Polymers

Polymers are more and more used in water's piping networks. The powerful characteristics and the simplicity of usage of these materials are the main raison for widely using them in the domestic and the industrial fields [16]. Choosing one or another are based on the usage conditions of temperature, pressure and environment. So, the HDPE and CPVC materials are one of the most chosen materials for water transport. The apparent advantage of CPVC is that it can stand a high temperature [17]. But judging these two materials must be done through the standard tests and evaluate their performance separately and compare them to have a clear idea about the performance of each material.

2) Composites

In today's world, Composite materials made of fibre-reinforced polymer (FRP) are a fast-growing material that is utilised in a variety of sectors, including aircraft, transportation, biomedical equipment, vehicles, and mining. Because of its less friction coefficient, better corrosion resistance, self-lubricating property, and high flexibility, FRP composite materials have become important in recent years [18]. It is anticipated that a 20% decrease in friction between machine components might result in financial gains.

C. Key Mechanical Properties of Interest

Mechanical properties of pipes explain how the pipes can be able to take its own internal pressure, external load and service conditions without collapsing. The major properties are yield strength, which determines the level of stress at which permanent deformation starts, ultimate tensile strength, which is the highest load that pipe material can withstand, and elastic modulus, which controls the level of stiffness of the material and also on it to deform elastically under load. Ductility, most commonly as Elongation, refers to the ability of the pipe to spare without breaking, and therefore is necessary when fabricating and tolerating overloads. Resistance to brittle fracture at low temperatures is determined by toughness and impact strength, and performance under cyclic pressure and thermal loading is determined by fatigue strength. In the case of high-temperature applications, creep resistance is a critical criterion, because it restricts the deformation over time. All these properties combine to regulate the design of pipes, the choice of the material and the long-term structural integrity.

1) Yield Strength

Yield strength is the approximate point on the stress strain curve. Up to the yield point, Hooke's Law is applicable as the stress strain relationship is linear. Load can be applied to a material; when the load is released, the material returns to its original shape. The slope of the line is the modulus of elasticity, E. Yielding occurs when the stress strain curve starts to deviate from a straight line.

2) Tensile Strength

Tensile strength or ultimate tensile strength is the maximum stress reached during a tension test. In ductile materials the ultimate measured strength commonly will be reached before fracture, with a lower stress level recorded at the point of fracture. Yield and tensile are measured along the stress side of the graph. In some structural designs, allowable stress is calculated from the tensile strength of a material, but for steel and ductile iron pipe it is not; yield should be used. It should be noted that the ratio of yield to tensile stress only shows the stress relationship and does not account for strain. It does not indicate the ability of the material to elongate or resist fracture.

3) Elongation

Elongation is a measurement of ductility. It is a measurement of the strain side of the graph and is usually measured as a percentage of permanent growth over a set length of the test specimen at fracture.

4) Toughness

Toughness is the ability of a material to deform plastically and absorb energy in the process before fracture. Toughness can be measured by taking the area under the stress strain curve. This is called the "material toughness". It can be seen that a material with low strength and high ductility does not have high toughness, and similarly a high strength low ductility material also has low toughness. It takes a combination of ductility and strength to achieve a high toughness.

III. Metallurgical Enhancement Techniques

The production of metals and their alloys will continue to increase in the coming years, mainly due to the growing demand for these products. Currently, the production of metals is a very important field of research, especially given their high prices and enormous demand. This field needs to be looked at from both the economic side, i.e., developing technologies that need less energy, and the ecological one, i.e., developing technologies that emit fewer pollutants and, at the same time, promote green technologies.

A. Heat Treatment Methods

A heating process is described as a process that seeks to increase the temperature of a material, and this may cause a change of properties of the material, with the use of different types of energy. The amount of power that is needed in this process depends on the principle of heat transfer applied and the intended temperature. The several heating methods involved are discussed below:

1) Annealing

Annealing is a popular post-process to enhance the mechanical strength and increase the percentage of crystallinity in FFF parts. Annealing is the process which requires the gentle heating of the material to its glass transition temperature or a thermodynamic temperature which is just higher than its melting temperature and then maintaining this temperature over a certain period then gradually letting the material cool [19], holding there for a specified time and then slowly allowing it to cool. This reheating and extended cooling increases the amount of large crystalline structures in the polymer and redistributes the stresses within the printed part leading to higher crystallinity, strength and stiffness.

2) Normalizing

Investment castings are not normally used directly, which needs normalizing or annealing heat treatment to improve the cutting performance. Depending on the actual production process of the foundry, normalizing treatment is applied to experimental AISI 441 investment casting to improve the microstructure and mechanical performance. However, the effects of normalizing treatment on AISI 441 prepared by investment casting processes lack relevant references [20]. Considering AISI 441 belongs to a kind of Ti-Nb micro alloyed stainless steel, the research of normalizing treatment effects on Ti and Nb micro alloyed stainless steels was reviewed. It can be found that the current studies of normalizing temperature and time on Ti-Nb micro alloyed stainless steels are relatively simple.

3) Quenching and Tempering

The quenching and tempering duration and temperatures have to be controlled to the precision to balance the constitutive microstructural and mechanical properties as desired. To date, although some scholars have carried out research on the heat treatment of some hull steels, the underlying mechanisms are not understood in detail [21]. The present work is concerned with specific elaboration of the strengthening mechanisms of high-strength EH47 hull steel subjected to different kinds of laboratory-based quenching and tempering processes.

B. Thermomechanical Processing

Thermomechanical treatment is a set of practices that included plastic deformation with heat treatment to improve properties of alloys especially in such processes as intermediate and final thermomechanical [22] processing. The intention behind these treatments is to enhance the density of dislocations in metals, and to enhance the toughness and the strength of high-strength aluminium alloys.

1) Hot-Rolling Process

Following the melting, the alloys were subjected to a heat treatment of homogenization to remove internal stresses, mitigate the imperfections generated by the cooling gradient of the melting furnace, and remove the potential segregates. This also made the alloys more ductile, preventing damage to the sample's rolling equipment and microcracks when submitted to the hot-rolling process. The hot-rolling process was then conducted to obtain a regular shape for Young's modulus measurements [23]. The samples were placed in a tubular furnace at around 1000 o C and sent through the hot-rolling equipment. This was done several times and each time the thickness was reduced by about 1 mm. A final thickness of 4 mm was reached.

2) Cold Pilgering

Cold pilfering is extensively used as a cold-working process of high quality seamless tubes, such as those of stainless steel, titanium alloys, or zirconium alloys. Such tubes are usually in need of high quality mechanical properties, quality surface [24], and close dimensional requirements. For zirconium alloy tubes used in nuclear reactor fuel cladding and titanium alloy tubes used in aircraft hydraulic lines, the permissible variations in outer and inner diameters, as well as wall thickness, are in the order of 10 μm [25]. The tube manufacturers are under intense pressure to have the right fabrication conditions to satisfy these demanding dimensional requirements. The various conditions in processes like feed rate, stroke speed, and turn angle have a major impact on the dimensional accuracy of tubes that undergo cold pilfering.

3) Severe Plastic Deformation (SPD)

Severe plastic deformation (SPD) is considered a materials processing technology. The deformation mode is the principal characteristic differentiating SPD techniques from common forming operations. For large plastic strains, deformation mode depends on the distribution of strain rates between continuum slip lines and can be varied from pure shear to simple shear. A normalized aspect of rigid rotation (the speed) is presented as a scalar, invariant and dimensionless coefficient of deformation mode. On this, simple shear gives the best mode of modifying structure and refining grains, pure shear is the best mode on forming operation. Figure 1 shows the expansion of pipe and cone.

Fig. 1. Expansion cone and pipe

IV. Surface Engineering Techniques

Surface engineering and coating technologies are important in improving corrosion, and wear resistance of materials applied in different industrial applications. They all are technologies that entail alteration of surface properties of materials to make them durable and better functioning within a harsh environment. Thermal spraying, electroplating, and chemical vapor deposition are some of the techniques that are usually used to add protective layers that form a barrier against corrosive compounds and abrasive forces. The choice of relevant materials in the case of coating is crucial because they should be composed of high hardness, adhesion, thermal [26], and chemical resistance. It has been seen to produce advanced coatings in terms of composite and nanostructured materials, which have better properties than the conventional coatings. Moreover, the surface engineering procedures such as shot peening and surface hardening can be used to add to the mechanical strength of the substrate, thus prolonging its life.

A. Coating Technologies

Coating processes have the highest portion of material enhancement since coating layers can reduce the cost and neglect the scarcity of materials as the thickness of coating layers rarely exceeds micrometres. This implies there is minimum material required to produce coating layers on a bulk of substrate materials. The properties that can be provided by the coatings include corrosion/wear resistance, improved surface hardness, deformed surface texture, thermal/electrical insulation, increased wettability, and hydrophobicity. Coating methods are available in a wide variety due to the enormous diversity of applications and needs in different fields. These processes consist of many different on-line/off-line parameters while giving way to many different outcomes in the form of material microstructure, effectiveness, suitability, and durability. However, coating methods are useful in specific applications according to the desired functionality among which corrosion and wear protection are the most important.

1) Physical Vapor Deposition (PVD) Coatin

PVD process is famous for offering corrosion and wear resistance and thin protective films on the surface of the materials that are exposed to corrosive media, and its applications range from decorative objects to industrial parts. The advantage of this method is that the mechanical, corrosion, and aesthetic properties of the coating layers could be adjusted on demand. In general, PVD is a process that takes place in a high vacuum and the solid/liquid materials transfer to a vapor phase followed by a metal vapor condensation, which creates a solid and dense film. The most known types of PVD are sputtering and evaporation. Since the coating layers created by PVD are thin in nature, there is always a need for multi-layered coatings while the materials selection should be considered carefully. Apart from its decorative applications, many PVD-coated parts serve as components that undergo a high rate of wear that causes abrasion on the surface and removes the coating layer. This phenomenon reduces corrosion resistance properties of the parts and makes them more susceptible to a corrosive media. Figure 2 represents a schematic view of different types of electron beam PVD machines.

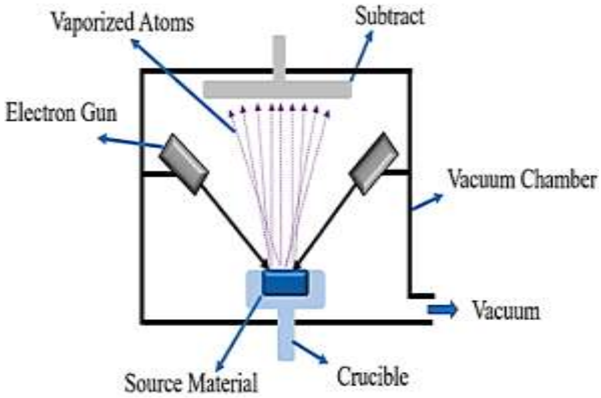

Fig. 2. Schematic view of a physical vapor deposition (PVD) machine using electron beam as the heat source

2) Chemical Vapor Deposition (CVD) Coating

Another type of vapor deposition is called CVD. This process undergoes a high vacuum and is widely used in the semiconductors industry providing a solid, high quality, and a high resistance coating layer on any substrate. CVD can be used for mechanical parts in constant contact, which need protection against corrosion and wear. In this process, the substrate, known as a wafer, would be exposed to a set of volatile material precursors where a chemical reaction creates a deposition layer on the surface of the material. However, some by-products of these chemical reactions, which are removed by constant airflow of the vacuum pump, can remain in the chamber. A schematic of the CVD setup is shown in Figure 3. The vaporized CVD materials are pumped from the right side and the heaters keep the temperature high enough to facilitate the chemical reaction between the substrate and vaporized materials.

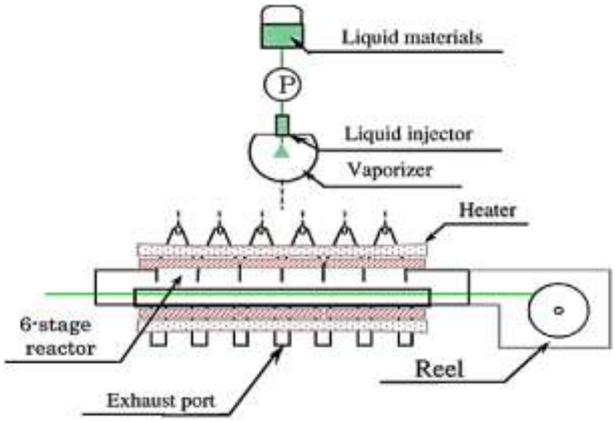

Fig. 3. Schematic chemical vapor deposition (CVD) setup, mechanical parts, and operation mechanism

3) Micro-Arc Oxidation (MAO) Coating

MAO process is known as a flexible process of coating regarding the composition of coating layers. The schematic of the process is illustrated in Figure 4. In general, MAO utilizes a high voltage difference between anode and cathode to generate micro-arcs as plasma channels. When these arcs hit the substrate, they melt a portion of the surface, depending on the intensity of the micro-arcs. At the same time, plasma channels release their pressure, which assists the deposition of coating materials in the working electrolyte on the substrate surface. The existing oxygen inside the electrolyte causes a chemical reaction of oxidation and provides oxides deposited on the surface of the substrate materials. The versatility of this process lies in the flexibility of combining desired elements and compounds as a solute in the working electrolyte.

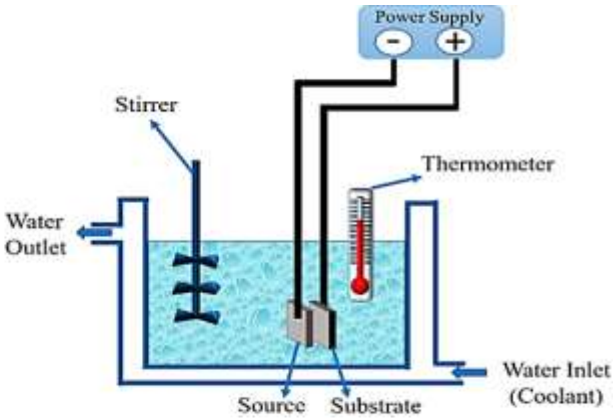

Fig. 4. Schematic view of micro-arc oxidation (MAO) process

B. Surface Modification Technologies

Surface modification methods have been developed in order to improve the mechanical properties of big workpieces with different dimensions and geometries. The surface of each workpiece can be reinforced by changing the microstructure (i.e., refining the grain size, inducing phase transformation, etc.) [27] and the surface stress state (mainly inducing compressive residual stresses), which will increase the fatigue, corrosion, and wear resistance of the whole part.

1) Shot Peening

The most used (and common) in the industry is the shot peening (SP) method which is simple, economical, and reliable. However, the induced roughness of around hundreds of micrometres is not suitable for certain applications, such as engines for the aerospace industry [28]. The SP technique is based on the collision between spherical particles (also known as bullets), mainly glass, metal, or ceramic material (like alumina “Al2O3”), and the surface of the part that is to be treated.

2) Sand Blasting

Sand blasting (SB) is a process that is used to refer to the process of smoothing, shaping, and cleaning hard surfaces through the application of high pressure solid particles to the surface of concern. SB equipment is usually housed in a chamber and mixed with air pressure, and then directed to the surface of the workpiece at a very high speed through a movable nozzle. This nozzle comes in a variety of shapes, sizes, and materials. Boron carbide is the most applied nozzle because it is highly resistant to abrasive wear. Tilghman invented this process in 1871, and it is used in today’s SP.

3) Grinding Treatment

Grinding (G-) is one of the finishing processes that gives high accuracy and a good surface finish. In this process, an abrasive product is used, and the material removal rate is very low. Usually, a rotating wheel that comes in to contact with a work surface is responsible for the operation [29]. This rotating wheel is made of abrasive grains that are bonded together. These abrasive grains act as cutting tools and remove tiny particles on the surface of the workpiece. Compared to other surface methods, this process is more expensive and should be used in conditions where is possible to control all parameters.

C. Thermal Methods

Thermal surface modification methods offer a wide range of techniques to enhance the properties of materials and most of them have been applied to MASS. These methods involve thermal processes that directly alter the properties (even microstructurally and mechanically) of the near surface of the workpiece treated [30]. One of the widely used thermal processes is laser surface texturing, which consists in utilizing high-energy laser beams to alter the microstructure of the surface of MASS. With this method, the shape, size, and location of microstructures, e.g., micro-dimples or micro-grooves, can be controlled precisely, and may be of great importance in determination of the tribological, mechanical and corrosion resistance properties of the material. Moreover, plastic deformation can be imposed on the surface of MASS by using cold working, rolling, bending or hammering, which leads to work-hardening and the enhancement of mechanical properties. The alteration of the surface properties of MASS components is a versatile technique to provide thermal surface modification techniques that could enhance the performance and the service life of MASS components in other applications.

1) Surface Heat Treatments

This group of thermal processes refers to treatments where the surface layer has the requirement of a higher hardness to be more wear resistant than the core. Surface heat treatments are conventional and effective surface modification techniques employed to enhance the properties of metallic alloys . The microstructure and composition of MASS can be accurately modified by exposing the surface of MASS to controlled heating and cooling. A carburizing is one of the most popular types of surface heat treatment in which a carbon-containing atmosphere is used on the MASS surface at high temperatures. The process enhances the solid diffusion of carbon atoms to the surface layer to form an outer layer, which is hardened and wear resistant, referred to as a carburized case. The other heat treatment method is the nitriding method that entails the addition of nitrogen to the surface of MASS. The nitrogen atoms also diffuse into the material and create a hard and corrosive resistant nitride layer. One can even use heat treatment to alter the residual stresses on the MASS surface. Thermal stress relief and residual stresses relaxation can be brought by controlled heating and following cooling and thus, enhances the dimension stability and fatigue resistance of the material.

2) Plasma Nitriding

The temperatures usually employed for nitriding treatments of low alloy and tool steels cannot be used for stainless steels because they would promote the precipitation of hard chromium (Cr) compounds (nitrides, carbides). As a consequence, the Cr-depleted matrix will not be able to form a protective passive film, and corrosion easily occurs. However, at lower temperatures, i.e., temperatures at which Cr diffusion is very low while interstitial atoms are able to diffuse (≤450 °C for nitriding), the formation of nitrides is inhibited and modified surface layers can be obtained. These layers consist mainly of a metastable supersaturated phase, named the expanded austenite or S phase, with a high hardness and good corrosion resistance. The nitriding of austenitic stainless steels (ASS) at temperatures ranging between 495 and 565 °C has been well established since 1970s. This nitriding is often conducted using plasma techniques, which allow for the removal of the surface oxide layers, and is known as plasma nitriding (PN). PN processes use discharging plasma in a combination of nitrogen and hydrogen gases [31]. The most important advantages of PN over conventional nitriding processes are reduced cycle times, controlled growth of the nitriding surface layer, elimination of the white layer, reduced distortion, there is no need to finish operations, there are no pores, and mechanical masks instead plating are pointed out. Nitride layers include scattered layers of $Fe_{2-3}N$, FeN, Fe_4N, and Fe_2N_3. The layer's spread is from tens to hundreds of microns, and they are ideal for improving wear resistance by optimizing the nitrogen to hydrogen ratio. Some of the extra layers can be removed and corrosion properties improved.

3) Laser Treatment

Laser treatment is a powerful and diverse method of surface modification that is applied to improve the characteristics of MASS. Hot beam laser technology allows one to make fine surface alterations with beams of very high energy leading to better surface features and performance. One of the uses of laser treatment is laser surface texturing (LST), in which laser ablation is controlled to form microstructures like micro-dimples, micro-grooves, or laser-induced periodic surface structures (LIPSS). These microstructures have a potential to play a considerable role in the tribological characteristics of the material i.e. friction, wear and lubrication behavior [32]. The other laser treatment method (LTM) is laser surface melting (LSM), which is a laser method where the surface of MASS is selectively melted to refine the grain structure, remove defects, and enhance the surface finish. Moreover, localized heating and subsequent controlled cooling which is achieved by laser heat treatment can be used to alter the phase composition and microstructure of MASS. This may either produce the desired phases (i.e. martensite) or refine the already existing phases resulting in an increase in mechanical properties. LTM gives a fine control of the treated region, depth as well as intensity and is therefore a useful method in modifying the surface characteristics of MASS to fit a particular application like automotive, aerospace, and medical.

V. LITERATURE REVIEW

The objective of pipeline material selection is to identify materials that offer low cost, extended lifespan, minimal maintenance costs, favourable hydraulic conditions, high durability against external loads, and excellent corrosion resistance. The following section provide the related studies on enhancement techniques for piping materials. Table I shows the focus, applications, materials, tools, and outcomes of the enhanced piping materials.

Yagci, Cadirci and Parlak (2025) examined a 6U-sized electronic card with high heat dissipation and evaluates the thermal performance of heat pipe-embedded cold plates in a conduction-cooled chassis. The goal is to achieve a design that combines the lightweight properties of aluminium with the superior thermal performance of copper. Three versions of heat pipe-embedded cold plates were analyzed: one with heat pipes embedded on the non-contact rear surface, another with heat pipes embedded on the contact surface extending straight to the card edge, and a third design with heat pipes bent to increase the condenser area. Initially, the variations in thermal resistance based on wedge-lock mechanism torque were examined for aluminium and copper cold plates, resulting in the selection of 1.2 Nm as the optimal torque for subsequent tests [33].

Bhayana et al. (2025) the pipeline method of coal transportation has numerous benefits, such as a cost-effective solution to transport high volumes of material, continuous operation, environmental benefits, reduced labour costs compared to traditional modes of transport like rail or truck. Moreover, coal slurry transport is crucial in many industrial applications, such as coal-fired power plants, steel manufacturing, coal liquefaction plants, mining operations, etc. Understanding the pressure drop characteristics of coal slurry behaviour inside the pipeline is vital for efficient system design and operation. In this experimental study, pilot-level pipe loop experiments were conducted to analyse the coal slurry flow behaviour inside a pilot plant test loop having sudden contractions, and bends [34].

Wang et al. (2024) proposed a detection method utilizing flexible magneto strictive transducers (FMsT) to excite ultrasonic torsional waves and applies it to the assessment of the welding status of HDPE pipes. The excitation of ultrasonic torsional waves is theoretically analyzed, exploring the viscoelastic HDPE pipe torsional wave propagation model and analyzing the theoretical features of attenuation and dispersion. Taking this as a theoretical basis, FMsT in HDPE pipes was designed, to excite ultrasonic torsional waves and propagate them along the pipes. This paper investigates the operational principles of FMsT, identifying HDPE defect characteristics through the reception of reflected echoes and transmitted waves. The experiments demonstrate that FMsT can successfully excite and detect ultrasonic torsional waves in HDPE pipes [35].

Li, Wang and Yang (2024) mechanical properties are one of the most critical indicators of hot-rolled seamless steel pipe. Seamless steel pipe served in harsh working environments for a long time, putting strict requirements on product quality and mechanical properties. Due to the "data barrier" between each production process's detection and control systems, the process data is impossible to use in predicting and improving product quality. To overcome the above difficulties, this research developed an industrial big data platform to realize a single steel pipe's data interconnection in the hot rolling line. The lower upper bound assesses framework of mechanical properties was established based on quantile regression long short-term memory networks (QRLSTM) model to meet the customer's requirements for the mechanical properties interval of each finished steel pipe [36].

Morgan et al. (2023) investigated the cooling performance of flexible pulsating heat pipes (PHPs) made from acrylic with a bend radius of ≈300 mm. The fabricated devices support two-phase, pulsating fluid flow inside the rectangular microchannels. Both water and ethanol are used as coolants, where local hot spots are generated by cobalt-alloy foil heaters inside the flexible PHPs. The PHP's dissipate the heat generated to the environment via copper condensers with controlled setpoint temperatures. Based on a heater surface area of ≈1.5 cm2and a condenser setpoint temperature of 25°C, the maximum heat flux observed for sustained and repeatable cooling with water and ethanol was 8 W /cm2 [37].

Latif et al. (2022) to reduce the dependency on non-renewable resources, high concentration nanocellulose structures are 3D printed, followed by freeze-drying. The freeze-dried structures are impregnated with a commercially available Epoxy resin via a widely used vacuum-assisted resin transfer melding process to manufacture nanocellulose-epoxy composites. The porosity, mechanical properties, and thermal stability of the 3D printed structures and composites are investigated by scanning electron microscope (SEM), three-point bending test, and thermal gravimetric analysis (TGA), respectively. The improved mechanical properties of the composites are due to porous free structures after infusion of an Epoxy resin, as confirmed by SEM. The thermal stability of the composites increased compared to freeze-dried structures, as confirmed by TGA [38].

TABLE I. SUMMARY OF EXISTING LITERATURE ON ENHANCEMENT TECHNIQUES IN PIPING MATERIALS

Author(s) & Year	Aim	Domain	Material	Tools / Methods	Key Findings
Yagci, Cadirci & Parlak (2025)	To evaluate the thermal performance of heat pipe-embedded cold plates for high heat dissipation electronic cards while combining lightweight aluminum with copper's thermal efficiency	Thermal management of electronics	Aluminum and copper cold plates with embedded heat pipes	Experimental thermal resistance analysis; wedge-lock torque variation	Optimal wedge-lock torque identified as 1.2 Nm; heat pipe-embedded designs significantly improved thermal performance while reducing weight
Bhayana et al. (2025)	To analyze pressure drop characteristics of coal slurry flow in pipelines with geometric disturbances	Slurry pipeline transport	Coal slurry	Pilot-scale pipe loop experiments with sudden contractions and bends	Pressure drop strongly influenced by pipe geometry; results support efficient design of industrial coal slurry transport systems
Wang et al. (2024)	To develop a non-destructive technique for evaluating welding quality of HDPE pipes	Non-destructive testing (NDT) of pipelines	HDPE pipes	Flexible magnetostrictive transducers (FMsT); ultrasonic torsional wave theory and experiments	FMsT successfully excited and detected torsional waves; defects identified through reflected and transmitted signals
Li, Wang & Yang (2024)	To predict and control mechanical properties of hot-rolled seamless steel pipes using industrial data	Smart manufacturing / steel pipe production	Hot-rolled seamless steel pipes	Industrial big data platform; Quantile Regression Long Short-Term Memory (QRLSTM) model	QRLSTM accurately predicted lower and upper bounds of mechanical properties, overcoming data isolation between production stages
Morgan et al. (2023)	To investigate cooling performance of flexible pulsating heat pipes under localized heating	Advanced thermal management	Acrylic PHPs; water and ethanol as working fluids	Experimental testing with foil heaters and copper condensers	Achieved maximum heat flux of 8 W/cm² at 25 °C condenser temperature; flexible PHPs showed stable cooling performance
Latif et al. (2022)	To develop sustainable nanocellulose-epoxy composites with improved mechanical and thermal properties	Sustainable materials and composites	Nanocellulose structures and epoxy resin	3D printing, freeze-drying, VARTM; SEM, bending test, TGA	Resin impregnation enhanced mechanical strength and thermal stability due to porous structure confirmed by SEM

VI. CONCLUSION AND FUTURE WORK

The primary causes of pipe failures include corrosion, imperfections and external interference that cause failure by leaching or bursting. By conducting an efficient inspection of defects, it is possible to prevent disasters provided that they are repaired in time. Pipe inspection methods are numerous and they include both the simple acts of inspection like the visual inspection to more intelligent methods of inspection like intelligent pigging. This paper has been a review of the state of art in piping materials, metallurgical enhancement processes and surface engineering processes that are applicable in the contemporary industrial uses. Comparison of metallic and non-metallic piping materials was done systematically on the basis of mechanical performance, resistance to corrosion and suitability in service. The main mechanical characteristics of the pipes such as strength, ductility and toughness were brought out as important aspects of choice and design of the material. It was demonstrated that advanced heat treatment, thermomechanical, and severe plastic deformation methods were able to enhance microstructural and mechanical properties to a significant degree. In addition, it was found that surface engineering solutions, including coating, surface modification, and thermal treatments, can be used as the effective methods of improving wear resistance, corrosion protection, and service life. Altogether, the research gives a complex framework that can be used to promote quality material selection and performance enhancement in challenging piping tasks.

The future studies will be based on experimental validation of the advanced piping materials during combined load of mechanical, thermal, and corrosive conditions. It will focus on hybrid materials, intelligent coating, assessment of long-term durability and data-based optimization methods to improve the reliability of pipelines, their sustainability, and lifecycle performance.

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