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Assessment of Nonhomogeneous Structures in Steel Contents in Terms of Fatigue Resistance Using Analytical Hierarchy Process

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ABSTRACT

Fatigue resistance of steel containing non-metallic inclusions (NMIs) varies widely, depending on many criteria; therefore, finding the most compromised types of NMIs is a sober objective that may significantly reduce severe damage and premature failure in many applications, such as bearings, gears, transmission shafts, etc. The multiple criteria decision-making methodologies have been used in this study to assess the more effective NMI types using the analytical hierarchy process by expert choice software. The five most common types of non-metallic inclusions selected are oxides, sulfides, carbides, silicates, and nitrides, based on different criteria: size, shape, distribution, mechanical properties, and quantity. The results showed that the oxide NMIs are the optimum type relative to the other four options regarding the fatigue resistance of about 35%, probably due to their spherical shape and small size. The most dominant criterion is mechanical properties, which have an effective percentage of 34.6% among the other criteria. It means that the reduction of other types rather than oxide NMIs probably enhances the fatigue resistance of the steel.

Keywords: nonmetallic inclusions, fatigue resistance, analytical hierarchy process, expert choice, multiple criteria decision making.

INTRODUCTION

Nonmetallic inclusions (NMIs) refer to minute, miscellaneous particles of nonmetallic substances that are inadvertently entangled within a metallic structure during the initial solidification stage and/or as a consequence of manufacturing procedures in addition to the additives to improve the solubility. Most of these inclusions are typically harder and more brittle than the metallic material bulk. NMIs can arise from various sources, including the raw materials used, the processing conditions and handling of the molten material. The effects of nonmetallic inclusions on material properties such as ductility, toughness, fatigue resistance, malleability, and corrosion resistance are gaining increased attention as industries demand for better-performing and reliability [1]. For that, the characterization, control, and management of nonmetallic inclusions have crucial essential for maintaining the high quality of metallic materials and ensuring their suitability for specific applications by guaranteeing the metal's reliability [2]. Numerous approaches exist to eliminate or reduce nonmetallic inclusions in the material matrix such as refining, filtration, degassing, and incorporating alloying components due to their negative role by increasing the cracking under cyclic loadings. The impact of various attributes such as type, composition, shape, and size of NMIs on fatigue resistance has been the subject of numerous scholarly publications; nonetheless, a definitive conclusion remains elusive [3–10]. Steel typically contains no more than 0.1% wt nonmetallic impurities; however, metal has a considerable number of inclusions due to its minute size. Steel can develop cracks and fatigue failure from nonmetallic impurities if NMIs subjected to deformation during rolling, forging, or stamping [11–13]. The chemical composition of steel, the molting process, and the quality of the steel (impurities content), play a crucial role in determining these characteristics. Several techniques have been recommended and put into practice for studying the effect of NMIs. They allow for the exact quantification of the inclusions in steel and alloys and for the determination of their composition and distribution. Furthermore, several physical and chemical factors can cause nonmetallic inclusions in the molten and solidified metal during metal production. "Natural" or "indigenous" describes nonmetallic inclusions that form due to various processes during the metal synthesis. All the impurities such as oxides, sulfides, nitrides, and phosphides are considered in the previous studies. NMIs aren't the only objects in the metal; there are also traces of slag, refractories, and casting mold (the metal comes into contact surfaces during the production). Reduced admixture dissolubility during cooling and consolidation is responsible for most inclusions' generating during the metal solidification. Most natural and foreign inclusions in steel can be filtered out by advances techniques in steelmaking technologies. However, inclusions are staying a general content in various steels and can vary widely and significantly the impact of the metal's properties [14–18]. In this study, five types of NMIs with five criteria (size, shape, distribution, mechanical properties, and quantity) have been evaluated to assess their role on the steel 'fatigue resistance.

Different inclusions have different effects on the mechanical properties of the engineering materials. Fatigue resistance is one of the most important properties of the engineering applications such as the shafts and bearings. The premature failure of wind turbine gearbox bearings has a considerable effect on the renewable energy cost [19] due to the consequences of the failure on the maintenance and components' replacement. There are a considerable number of published researches pointed out the NMIs as the main source of trigging the fatigue failure initiation [1, 4, 20]. As an example, the fatigue life of prematurely failed bearings in wind turbines is always within 10% to 25% of the bearing design life [19]. Al-Bedhany et al. [21] investigated the surface of failed wind turbine planetary bearings after one year and two months compared with 20 years according to the design standard. Figure 1 presents a surface fractography of three failed wind turbine bearings due to fatigue. When the inclusions close to the contact surface; they may cause surface crack initiation which advance to the final failure mode; however, the subsurface crack initiation from nonmetallic inclusions and carbides also reported in a considerable number of studies [22, 23]. The study of subsurface cracking for test discs showed the considerable role of NMIs on the fatigue life [19]. For real wind turbine bearing, the subsurface investigation showed the considerable role on NMIs in the premature failure of the turbine gearbox bearings [22, 24].

In this study, the role of various types of NMIs on fatigue life has been studied and evaluated to

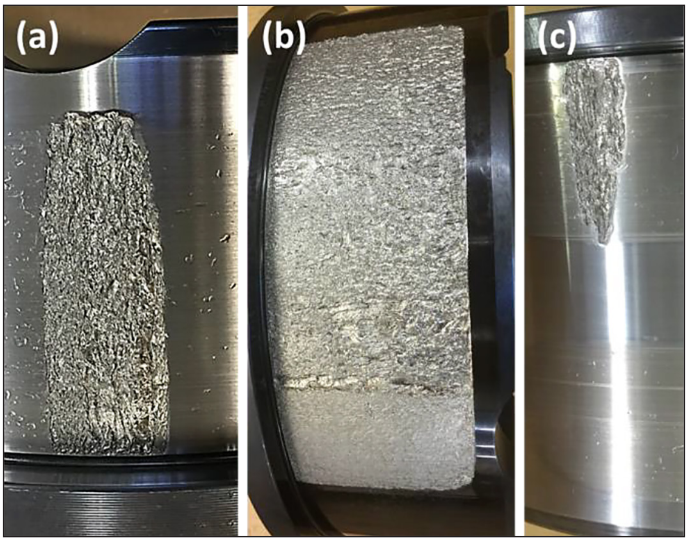

Fig. 1. Fractography of three failed bearings by fatigue (a) uncoated single row cylindrical roller bearing, (b) failed bearing coated with black oxide, (c) double row uncoated failed bearing

specify which inclusion' type has much harmful effect on the fatigue life. This to recommend the manufacturer to avoid this type of inclusion within the steel subjecting to fatigue loading. Inclusions consisting oxides of calcium and aluminum, such as $CaO-Al_2O_3$ and $Al_2O_3-SiO_2$, can be beneficial in promoting fatigue resistance in steel probably due to their mechanical properties and shape; however, their quantity also should be controlled.

METHODOLOGY

Three stages have been conducted regarding the overall research methodology, as follows:

1. Utilizing the role of NMIs in the previous studies to consider the following guides:
   a) The most corresponding categorizing approach of NMIs,
   b) Analyzing the main criteria that affect the differential process in terms of fatigue resistance, and
   c) The comparison of scores for each criterion concerning the assessment's primary goal, evaluating the NMI types' differential scores for each criterion, which depend on how the previous research pointed out a specific NMI type as more harmful than the others.
2. Build up the analytical hierarchy process (AHP) structure and analyze its matrices using expert choice (EC) software to find the performance sensitivity results of the assessment process i.e., the interactive effect of each criterion on the other one, and
3. Results' discussion to conclude the most compromised solution of the NMI type in terms of fatigue resistance i.e., getting the individual score for each criterion which represent the effect percentage.

Formation and effects of NMIs

Inclusions are commonly referred to as "slag inclusions", "macro-slags," and "micro-slags". These terminologies are indicative of their respective origins and characteristics. Nonetheless, this assertion lacks universality as the majority of inclusions are endogenously generated within the steel and, consequently, are impervious to any effects of the present of slag on the surface of the steel. In steel production, the manipulation of metallurgical processes is focused on achieving prescribed levels of inclusions and their related properties [25]. This process holds immense significance, with a critical emphasis on the inclusion reproducibility in the steel production stages to avoid unnecessary elaboration and ensure optimal steel quality. The formation of inclusions occurs at various stages in the steel production process. During the molten state of steel, primary inclusions form then, they are separated through the manufacturing processes [26]. The presence of secondary inclusions has been detected in metal cast stage. Some of the latter inclusions have dimensions smaller than 1 μm and tend to form during the solidification process and can impart beneficial properties to steel. Inclusions can significantly influence the microstructural characteristics of metals, resulting in improvements in some properties but concomitant deterioration in others. The diverse characteristics, such as weldability, fatigue strength, surface roughness, corrosive properties, ductility, and machinability, of a material are significantly affected by the nature of inclusions, encompassing their dimensions and composition, notably when the inclusion size exceeding the range of 10–15 μm [27].

Nonmetallic inclusions

Nonmetallic inclusions refer to a wide range of particles or substances in a metallic material that are not metal [28, 29]. The following items elucidate some general categories of nonmetallic inclusions.

1. **Oxides**: These are the most common nonmetallic inclusions and can form during steelmaking, casting, and other processing steps. The most common oxide is alumina, but other oxides, such as silica, magnesia, and titania, can also be formed. They are commonly found in steel and can affect the mechanicals properties, including the ductility, toughness, and fatigue resistance [30, 31]. Oxide inclusions can also form cracks and propagate them in the material, making them an essential factor in material design and processing. Oxide inclusions can be classified according to their construction as Simple oxide inclusions such as – FeO, MnO, Cr_2O_3, SiO_2, Al_2O_3, TiO_2, and compound oxide inclusions – $FeO·Fe_2O_3$, $FeO·Al_2O_3$, $FeO·Cr_2O_3$, $MgO·Al_2O_3$, $2FeO·SiO_2$ and others. Oxygen inclusions can be broadly classified according to their mineral concentration as follows:

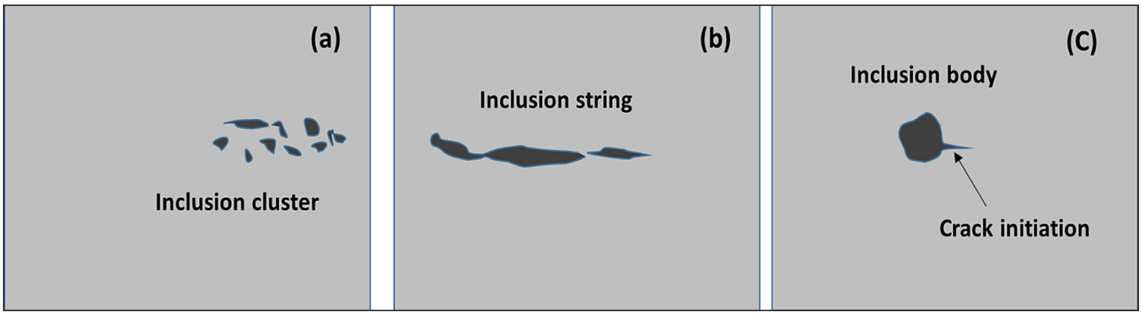

Fig. 2. Schematic of oxides inclusions (a) Al_2O_3, (b) $SiO_2.Al_2O_3$, and (c) $Al_2O_3.CaO$

- Oxides not bound to anything else are called "free oxides",
- Oxides of titanium and zirconium, known as "spinels".

The morphology of oxide NMIs includes the following shapes, as can be seen in Figure 2, however, the inclusions' sizes are widely different depending on the steel manufacturing technologies. NMIs have the following types depending on their shape:

a) Angular or irregular shape: These inclusions are usually formed during deoxidation or due to the presence of refractory compounds,
b) Globular or rounded shape: These inclusions are formed due to reactive elements like calcium and magnesium or the reaction of molten steel with the refractory lining,
c) Elongated or stringer shape: These inclusions are formed due to the elongation shape of the large inclusions or due to the presence of barium in steel, and
d) Platelet shape: These inclusions are formed due to aluminum in steel, forming aluminum oxide platelets during can be formed throughout the solidification stage [32].

2. **Sulfides**: These inclusions can form when sulfur is present in a metal, such as in the case of steelmaking with sulfur-containing raw materials. Sulfides are typical inclusions in steel and can harm its mechanical properties. This type can be either single-phase or multiphase sulfide. (Single phase (Simple): FeS, MnS, Al_2S_3, CaS, MgS, Zr_2S_3 and CuS. The second type is multi-phase (compound) inclusions: FeS·FeO, MnS·MnO, and others). The most common morphology of sulfide NMIs is an elongated, elliptical, or stringer shape. These inclusions are typically grey elongated in one or more directions according to the method of their formation. All steels have manganese added to them to stop the production of iron sulfide. Due to their high plasticity (deformable) at high working temperatures, manganese sulfides are extended during the hot working process. The aspect ratio of manganese sulfides (length to width ratio), can be lowered by adding certain elements to influence the morphology of inclusions and so alter the level of material's hot plasticity. The maximum sulfur content for common carbon steel grades is 0.050% wt. Sulfur content in alloy steels is typically kept below 0.040% wt [33]. At high temperatures,

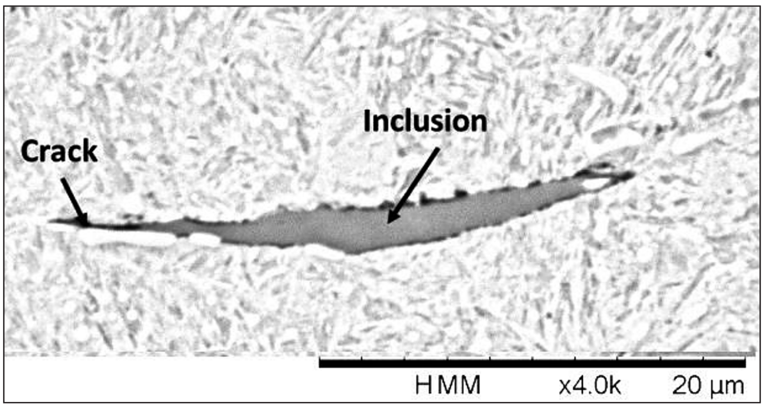

Fig. 3. A large MnS inclusion present in a hardened steel microstructure

sulfur can cause steel to become red, and brittle. Adding sulfur to steel in concentrations of more than 0.25% wt is common practice to enhance its machinability, however, it is often thought to reduce steel's beneficial mechanical qualities [34]. MnS inclusions could be formed after hot-working or annealing at high temperatures for brief periods. It is poorly soluble in iron and produces globular inclusions in pale grey, sometimes slate-colored inclusions, as can be seen in Figure 3.

3. **Nitrides**: Nitrides can precipitate either during the liquid steel phase of an alloyed steel or after the steel has solidified. The coarse nitrides often significantly degrade the steel characteristics [35]. These inclusions are form when nitrogen is introduced into the metal during the processing to improve mechanical properties, such as strength and hardness. Common nitrides include aluminum nitride, titanium nitride, and zirconium nitride. Alloyed steel contains strong nitride-generating elements with titanium, aluminum, vanadium, cerium, and others (ZrN, TiN, AlN, CeN, and others as simple inclusions, however; compound inclusions such as Nb(C, N), V(C, N), and others). The Nitrides are typically found in high-strength steels that also contain elements having strong affinity for nitrogen. The morphology and shape of nitride nonmetallic inclusions can vary based on their composition, size, and formation conditions. Generally, they can have a spherical or irregular shape and can range in size from several micrometers to millimeters [29].
4. **Silicates**: These inclusions are formed from the reaction between the metal and silica-containing materials, such as refractory materials used in furnace linings. Depending on the specific processing conditions, silicates can have different chemical compositions and morphologies. One highly representative instance of controlling inclusions occurs through the intricate process of deoxidation, wherein the addition of silicon and manganese is employed. The acid open hearth process (OHP) was conventionally deemed customary, in harmony with implementing an acid silica furnace lining. The OHP method was utilized for approximately a century following its inception until the 1970s to fabricate steel grades that required limited inclusions, specifically in producing high-performance bearing steels. During that period, the production process transitioned towards utilizing the ladle furnace-vacuum treatment pathway and incorporating the Al-deoxidation methodology. The Si-Mn deoxidation process is still used because of the benefits of silicate inclusions, which can be used in many different products. The attainment of exceptional steel cleanliness is paramount in wire applications that require a high degree of rigor. Different types of inclusions and their characteristic of steel must not be rigid brittle but rather malleable and capable of being drawn out into thin, innocuous stripes during the rolling shaping conditions. The deoxidation process involving manganese and silicon does not exhibit sufficient efficiency in reducing oxygen levels compared to aluminum deoxidation. Enhancing the deoxidation potential is imperative to meet the stringent cleanliness criteria of steels [36]. Using SiO_2-CaO-Al_2O_3-MgO), slag makes it possible to increase the effectiveness of deoxidizing silicon by making it less likely to oxides. This can be accomplished by establishing intimate contact between the steel and slag with notably low silica activity [36, 37]. Silicates can be found in glasses that resemble steel, are made from either pure SiO_2 or SiO_2 combining with trace amounts of iron, manganese, chromium, aluminum, and tungsten oxides. Among the nonmetallic inclusions, silicates represent the largest group. Nonmetallic inclusions in liquid steel can be either solid or liquid. The melting point of inclusion is a determining factor. The most common shapes observed in steel include irregularly shaped globules, elongated particles, and plate-like particles, as can be seen in Figure 4. When the percentage of silicate is relatively high; the morphology of the inclusions has similar shape to that of the sulfide type; however, silicate inclusions can be recognized from the color of the inclusions where the silicate inclusions have darker color compared with the sulfide type having usually light grey color. The rate of cooling, heat treatment, and the presence of additional elements like calcium or aluminum can all affect the inclusion precise shape. Phosphorus materials make up only a trace percentage of metal inclusions. Silicates seriously harm the steel properties, especially if it will later require heat treatment [37].

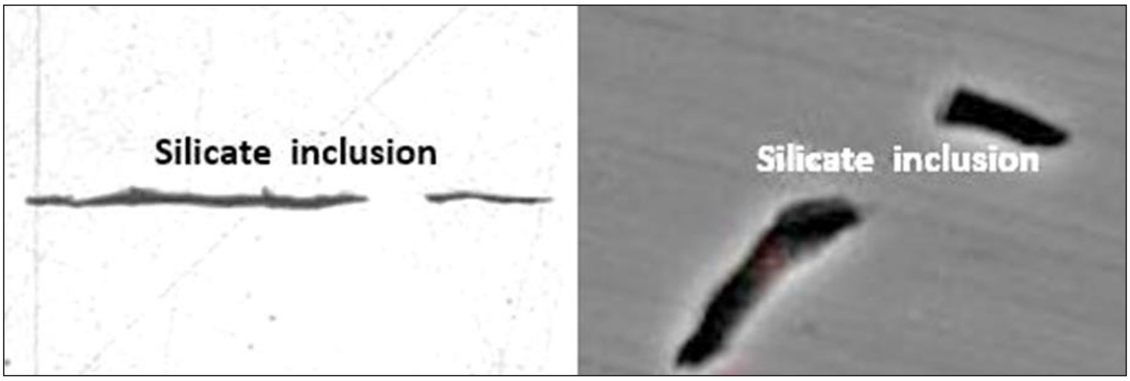

Fig. 4. Typical morphology of silicate inclusions

Carbides

Carbides are formed when carbon is introduced into the metal during steelmaking, casting, or processing to increase hardness and wear resistance. Typical carbides include: iron carbide, tungsten carbide, and titanium carbide. Their shapes can vary depending on type and composition of the additives throughout the introducing stage. Some common shapes include acicular (needle-like), globular (rounded or spherical), angular (sharp-edged), and irregular shapes. The range of size of carbide can also vary from micro-level (fine particles) to more significant, coarser particles [38–41]. Most carbide in bearing steel are stiffer than their surrounding bulk material and harm the material properties such as ductility, toughness, and impact strength. Furthermore, carbide can also provide benefits such as wear resistance and high-temperature properties.

Other nonhomogeneous structures

Not only the NMIs has a considerable effect on the component' fatigue life which is very important for different engineering applications such as the bearings, shafts and gears but also the nonhomogeneous structures such as the carbides. Carbide is a microstructure produced in the material bulk during the casting process and/or throughout the heat treatment stage. It has been found that, the carbides have a higher hardness compared with bulk and there is a stress concentration around these carbides that may work as the fatigue trigger sites which leading to the early fatigue failure in several engineering applications [42, 43].

Carbides usually associated with voids, which represent the important crack trigger under fatigue loading in large scale bearings such as the bearings used in wind turbine gearboxes. For the above reasons; carbide will also be considered throughout the analyses of nonhomogeneous' role on fatigue resistance of steels.

NMIs types based on their origin

The presence and magnitude of nonmetallic inclusions within a metallic material are heavily contingent upon various factors encompassing processing conditions, raw materials, and quality control measures. The reduction of nonmetallic inclusions significantly impacts the end product's optimal quality and subsequent performance [44]. Glass-ceramic phases embedded in a steel-metal matrix are what introduced some NMIs. According to traditional classification, NMIs can be distinguished into two main classes as a function of their origin as (i) endogenous and (ii) exogenous:

1. The endogenous inclusions form by precipitation within the liquid phase due to the decreased solubility of the chemical species contained in the steels. This class of nonmetallic inclusions cannot be eliminated from the steel. However, the decrease in their volume fraction and average size has to be taken under strict control to avoid activating the negative phenomena.
2. The exogenous inclusions result from trapping non-metallic materials from slag, refractory fragments, or rising and covering powders used to protect the steel and avoid sticking during the casting. The non-metallic inclusions of this class can be found in large sizes, and their origin cannot be immediately recognized but, their presence can strongly compromise the microstructural soundness of the steel and the associated mechanical reliability.

The standard classification of NMIs

The standard diagrams categorized NMIs into five primary groups, labeled A, B, C, D, and DS, guided by the conformation and dispersion of the inclusions [24, 45]. These five categories embody the prevailing manifestations and forms of inclusions that are frequently perceived.

- The entities in Group A, classified as sulfide types, exhibit a high degree of malleability and exist as discrete gray particles characterized by a broad spectrum of aspect ratios. Typically, the particles feature rounded termini.
- Group B, characterized by an aluminate type, possesses a multitude of non-deformable, angular particles with a low aspect ratio (typically < 3), colored black or bluish. The sample at hand contains at least 3 such particles, all exhibiting alignment in the direction of deformation.
- Group C, characterized as a silicate type exhibits a high degree of malleability and composed of discrete black or dark gray particles and possessing various aspect ratios, typically exceeding three furthermore exhibiting pointed tips.
- Group D comprises globular oxide-type particles characterized by their non-deformable nature, angular or circular shape, low aspect ratio, which typically does not exceed 3, black or bluish color, and random dispersion.
- Group DS (monolithic spheroidal morphology) comprises a uniformly shaped, discoid, or nearly discoid solitary entity and possessing a diameter often exceeding 13 μm [45].

The impact of the morphology of the inclusions on the machinability and properties of steel presents a significant factor for consideration. The inclusions are capable of facile elongation in the direction of rolling. Several instances of ductile inclusions, such as MnS, CaSi, and MnSi, exhibit a substantial component of SiO_2. Figure 5 recognizes the main four groups of inclusions depending on the inclusions' density and frequency as presented in ISO 4967 [45]. The methodology of inspection in this standard depends on calculating the cleanliness of a material by evaluating an inspection area of 0.71×0.71 mm from a specimen taken from a specific location for inclusion types A, B and C. However, for type D, only the lengths of the inclusion inside the inspection area are considered (more details can be seen in [45]).

NMIs properties and effects

Metal with hard inclusions rolled often shows impurities in the rolling direction, such as calcium aluminates, small Al_2O_3 inclusions, and MgO-Al_2O_3 spineless. To avoid crack-initiating points, steel applications with high fatigue demands minimize inclusions. Low Ca and Mg content in alloys and deoxidants help reducing the number of (D) inclusions [27]. During the metalworking process, NMIs exhibit one of four distinct inclusion deformations. The following behaviors and characteristics of NMIs can be recognized:

- Distortion analogous to that of the steel matrix. These inclusions are flexible and highly elongated along the rolling axis. Manganese sulfides and breakable silicates are the common types of this category.
- Inclusions made of a hard, brittle material that shatters into stringers or individual pieces during the metalworking process. Clusters and inclusions of alumina are examples of this category [46].

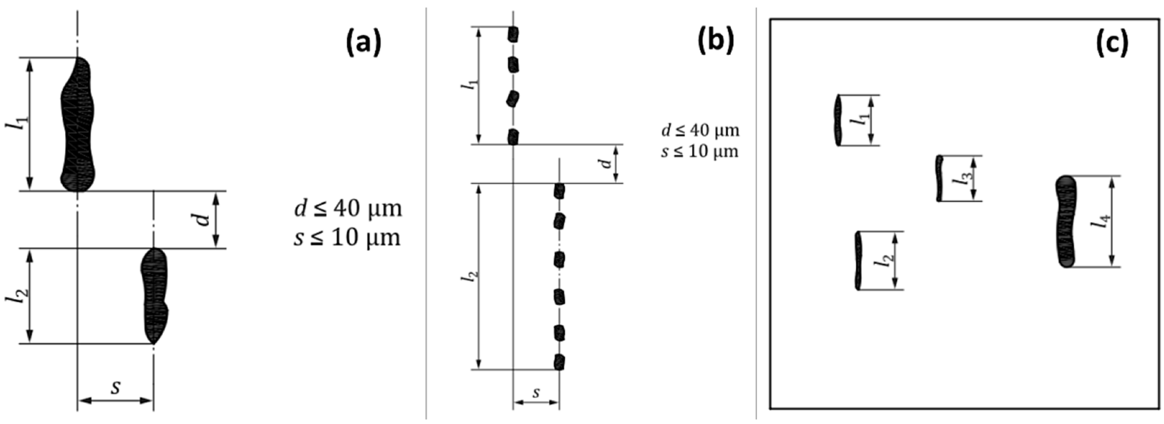

Fig. 5. Various inclusion types (a) A and C types inclusions, (b) B type inclusion (c) D type inclusions [45]

- Inclusions with a rigid center and a pliable periphery. These inclusions typically exhibit ductile behavior at small deformations, but at larger deformations, they thicken in the middle and lengthen at the ends, such as confounding multi-phase inclusions.

Nonmetallic inclusions in steel typically encompass a range of substances, such as oxides, sulfides, and oxy-sulfides. However, they typically manifest in solid steel and exert significant influences on the material's properties through mechanisms such as grain refinement and precipitation strengthening [47]. The antecedent faction pertains to the inclusions occurs through the reactions in the liquefying or congealing steel. At the same time, the latter encompasses the inclusions that ensue from the mechanical integration of slags, refractories, or other substances that interact with the molten steel [48]. There is a dichotomy between stable and unstable non-metallic inclusions. Inclusions that are easily dissolved by weak acids (those with a concentration of < 10%) are considered unstable. Iron and manganese sulfides, as well as some free oxides, are unstable inclusions. The current volume of steel manufacturing allows for diversification into other inclusions. However, the inclusion content in various steel varies widely and significantly affects the metal's properties [49]. As can be seen in Table 1 there are different values of thermal expansion coefficients (α), Young's modulus (E), and Poisson's ratio (ν) for various types of inclusions. Juvonen [48] illustrated the proclivity towards developing internal stresses in the vicinity of inclusions caused by discrepancies in coefficients of thermal expansion of the inclusions and the matrix within multiple varieties of inclusions in bearing steel. The problem is further complicated by the mutual solubility of iron oxides and sulfides with certain alloying elements, such as manganese. Consequently, to produce high-quality steel, it may imperative to reduce the levels of oxygen and sulfur in the steel. Various elements currently commercially available and deemed acceptable constituents of steel, such as silicon, manganese, and aluminum, exhibit a pronounced inclination towards oxygen. Due to their introducing, these elements can be efficaciously employed

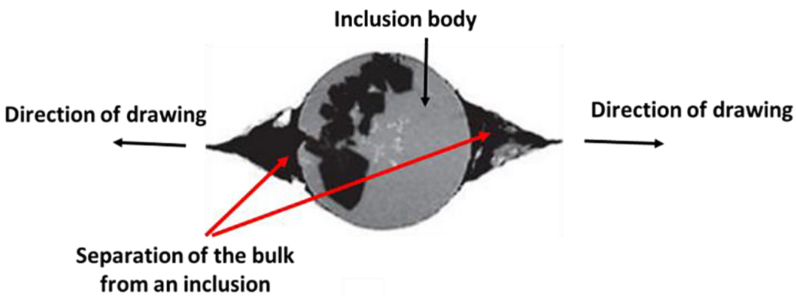

Fig. 6. Cold drawing steel wire created voids at the ends of a hard, massive, non-deformable NMI – adapted from [47]

Table 1. Values of thermal expansion coefficients (α), Young's modulus (E), and Poisson's ratio (ν) for the types of inclusions – modified from [48]

Inclusion type	Inclusion	$\alpha \times 10^{-6}$/°C	E (GPa)	ν
Sulfides	MnS	18.1	69-138	0.3
	CaS	14.7		
Calcium aluminates	$CaS \cdot 6Al_2O_3$	8.8	113	0.234
	$CaS \cdot 2Al_2O_3$	5.0		
	$CaO \cdot Al_2O_3$	6.5		
	$12CaO \cdot 7Al_2O_3$	7.6		
	$3CaO \cdot Al_2O_3$	10.0		
Alumina	Al_2O_3	8.0	389	0.250
Nitrides	TiN	9.4	317	0.192
Oxides	MnO	14.1	178	0.306
	CaO	13.5	306	0.178
	FeO	14.2	183	0.210

as deoxidizers in liquid steel, readily creating nonmetallic deoxidation products [7]. These products can serve as crucial oxide nonmetallic Inclusions (NMIs). In the context of sulfur, it is noteworthy that those elements demonstrate low solubility in iron, such as Ca and Mg, or rare earth evince adequate affinity towards sulfur to create non-metallic sulfides at liquid metal temperatures [50, 51]. The majority of sulfur present in steel must be eliminated from the solution through slag refining. In contrast, the remaining amount is eliminated through precipitation reactions, which predominantly occur during solidification [4, 52].

High temperatures affect ductility, formability, and toughness. Depending on the relative flexibility of the material, NMIs can produce voids (separation of material) and stress concentrators even when they do not lead to material failure, as concluded by Hollapa and Wijk [47] (Fig. 6). Moreover, the variation of Coefficient of Thermal Expansion (CTE) can facilitate NMIs-matrix dissociation. TiN, on the other hand, exhibits no separation at the TiN-steel under fatigue contact due to its robust interaction with the matrix [10, 21, 40, 53].

Criteria of comparison

The following are the main criteria by which the effect of impurities on fatigue resistance can be indicated [27].

1. **Size**: The size of inclusions is critical factor in determining their effect on fatigue resistance. Large inclusions can act as stress concentrators and represent a pre-cracking that promote to morphology and initiate cracks. On the other hand, minor inclusions may not have as much of an impact [54].
2. **Shape (morphology)**: The shape of inclusions can also affect their impact on fatigue resistance. Inclusions with sharp edges or corners are more likely to act as stress concentrators and initiate cracks. non-metallic inclusions can have various morphologic shapes, including spherical, elongated, irregular, and dendritic. The shape of the inclusion depends on various factors such as the composition of the inclusion, processing conditions, and cooling rate [55]. Spherical inclusions are typically formed during solidification, while elongated or dendritic inclusions can be formed during the deformation or stirring of the metal. Irregular-shaped inclusions are the result of the interaction between the inclusion and the surrounding molten metal. The longer region of the material that will be subjected to stress concentration in steels with extended NMIs is larger than those found in highly clean steel (such as bearing steels). This lead to suggest that, these NMIs may have an influence larger than the expected [56].
3. **Distribution**: The distribution of inclusions within the material can also affect its fatigue resistance. Clustering of inclusions can result in local areas of weakness and reduce the material's overall fatigue resistance, especially when these clusters locate at a critical location where high-stress maybe introduced.
4. **Mechanical properties**: The mechanical properties of inclusions affect their impact on fatigue resistance. Inclusions that are harder or more brittle than the surrounding material can act as stress concentrators and initiate cracks. Mechanical properties like strength, fatigue, ductility, brittleness, fracture toughness, hot shortness and tearing, welding properties, machinability, surface polishing, and finishing in addition to corrosion can all be affected by the amount and type of non-metallic inclusions present in the steel [47]. The chances of achieving the desired attributes can be increased by manipulating the inclusions' composition, size, and distribution. The mechanical properties are directly affected by the inclusions' composition. This means that the inclusions' behavior during metalworking will vary according on their composition and structure.
5. **Quantity (density)**: The material's fatigue resistance affects by the number of inclusions. Higher density levels of inclusions can result in a greater likelihood of crack initiation and propagation due to high probability of connecting the cluster inclusions to form a crack in the primary stage. The difference between quantity and distribution is that, the latter represents the locations of the inclusions in the clusters and the locational relation among these clusters; however, the former represents the number of inclusions in each cluster.

Steels cleanliness (SC)

The term "clean steel" generally refers to steel that has few or no inclusions. Over time, improvements in steelmaking processes have reduced the number of harmful substances in the final product. Oxygen, sulfur, phosphorus, and hydrogen are examples of such undesired substances. The efforts to increase the steel cleanliness have often focused on reducing oxides and sulfides because big oxide inclusions are usually undesirable, it is preferable to have as little oxygen in the steel as feasible. However, a high fatigue strength and a low oxygen content are not always associated [57]. Neither is a smaller oxide size, the steel's purity can be somewhat characterized by its oxygen and sulfur concentrations [48]. There are a number of different options for producing ultra-clean or super-clean steel outside the ones that are considered "conventional" today. Electro-slag re-melting (ESR) is one of the most prevalent, along with vacuum arc re-melting and electron beam melting to improve the steel cleanliness. Ingots are re-melted, and the molten drops are then solidified in a water-cooled mold. When comparing ESR to traditional refining techniques, secondary metallurgy typically favors the former [47]. This has led to a dramatic rise in the cleanliness of steel but, "clean" steel also refers to the kind, size, and distribution of the inclusions that certain impurities (O, S, N) create in steel. As a result, understanding the occurrences and behavior of inclusions along the entire process path is crucial. The importance of process modeling and "online" computer utilization for inclusion control, along with new measuring instruments, will grow in significance in the near future [47]. Increasing the steel cleanliness is a costly process despite its positive impact on fatigue resistance and increasing the cleanliness depends on the application of the steel.

Analytical hierarchy process

Analytical hierarchy process is a multi-criteria decision-making method that helps selecting the best alternative among multiple options by decomposing complex decisions into smaller, more manageable components. AHP evaluates alternatives based on a set of criteria and provides a mathematical framework to derive the relative importance of each criterion and the alternatives' ranking. In this method, decision-makers identify the criteria for evaluation and assign numerical weights that reflect the relative importance of each criterion. Alternatives are also evaluated against each criterion and compared pairwise to determine their relative importance. Finally, the method calculates a priority vector for each criterion and alternative, ranking alternatives that satisfy all the criteria. One of the most popular tools in AHP is expert choice software, which accelerates and adjusts the math process of AHP matrices. AHP is widely used in various fields, such as engineering, management, and environmental sciences, for decision-making, prioritization, and resource allocation. It is a helpful tool for structuring and analyzing complex decision problems where multiple and often conflicting criteria should be considered. The entrance for applying AHP is the assignment of its three components: goal, criteria (with sub-criteria), and options (or alternatives), as can be seen in Figure 7.

RESULTS

Inclusions' size, shape, distributions, mechanical properties, and quantities can all play a considerable role in the materials' resistance to fatigue. The relative importance of each factor may depend on the particular application and the specific context in which the material will be used. For example, in some applications, such as components subjected to high-stress or

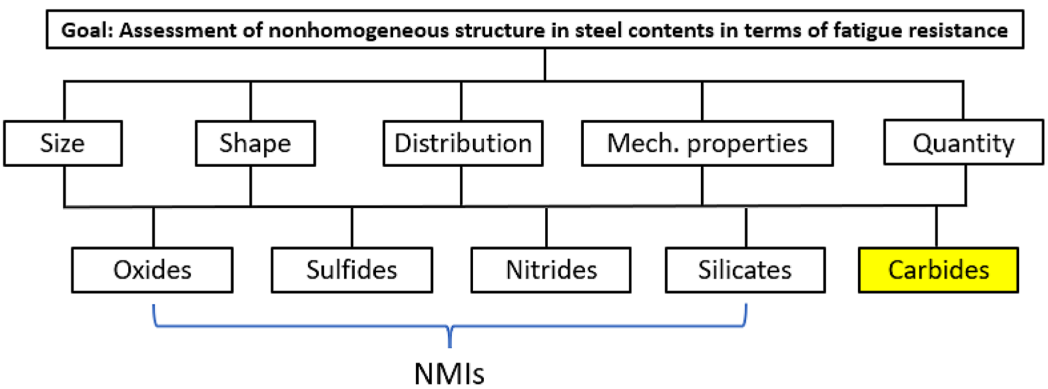

Fig. 7. AHP structure (goal, criteria, and options)

	Size	Shape	Distribution	Mech. Prop.	Quantity
Size		3.0	3.0	4.0	3.0
Shape			3.0	3.0	2.0
Distribution				3.0	3.0
Mech. Prop.					1.0
Quantity	Incon: 0.07				

Fig. 8. Comparison of the criteria with respect to the main goal of the assessment

	Oxides	Sulfides	Nitrides	Carbides	Silicates
Oxides		4.0	3.0	2.0	3.0
Sulfides			3.0	1.0	3.0
Nitrides				2.0	2.0
Carbides					2.0
Silicates	Incon: 0.06				

Fig. 9. Comparison of the NMIs types with respect to their sizes

	Oxides	Sulfides	Nitrides	Carbides	Silicates
Oxides		2.0	2.0	2.0	3.0
Sulfides			2.0	3.0	3.0
Nitrides				2.0	3.0
Carbides					2.0
Silicates	Incon: 0.04				

Fig. 10. Comparison of the NMIs types with respect to their shapes

	Oxides	Sulfides	Nitrides	Carbides	Silicates
Oxides		2.0	3.0	2.0	3.0
Sulfides			3.0	2.0	3.0
Nitrides				3.0	2.0
Carbides					3.0
Silicates	Incon: 0.04				

Fig. 11. Comparison of the NMIs types with respect to their distributions

	Oxides	Sulfides	Nitrides	Carbides	Silicates
Oxides		2.0	2.0	3.0	3.0
Sulfides			2.0	1.0	3.0
Nitrides				2.0	2.0
Carbides					1.0
Silicates	Incon: 0.05				

Fig. 12. Comparison of the NMIs types with respect to their mechanical properties

	Oxides	Sulfides	Nitrides	Carbides	Silicates
Oxides		2.0	2.0	2.0	2.0
Sulfides			3.0	2.0	1.0
Nitrides				3.0	2.0
Carbides					3.0
Silicates	Incon: 0.05				

Fig. 13. Comparison of the NMIs types with respect to their quantities

high-temperature environments, the mechanical properties and sizes of inclusions may be the most critical factors for their resistance to cracking. In other cases, such as machining or wear applications, the shape and quantity of inclusions may be more important. However, in a relatively differential manner under natural conditions, the results of the AHP assessment regarding the comparison criteria elements revealed that the mechanical properties of NMIs are the most dominant compared to the others at about 34.6%, as can be seen in Figures 8 and 15. Moreover, the type of inclusions can also influence the behavior of the surrounding matrix material and the way it responds to applied loads and stresses. Therefore, the specific factors governing the fatigue resistance of inclusions can vary widely and require careful assessment for each specific application.

The best inclusion type for a particular application depends on various factors, such as the type of material used, the intended use, and the environmental conditions it will be subjected to. Relatively, it has been observed that the oxide NMIs' type seems to be the most optimal option regarding the compromised criteria at about 35%, as shown as pairwise comparison matrices in Figures 9–15. That being said, oxides are generally less likely to cause cracking under fatigue loading compared to other types of inclusions. This may because the oxides typically have a lower solubility in metals and alloys and tend to remain stable under high-temperature and high-stress conditions in addition to high bonding with the steel matrix. It means that the rest types may have a higher solubility and may dissolve or deform under such conditions, leading to cracking and failure. Moreover,

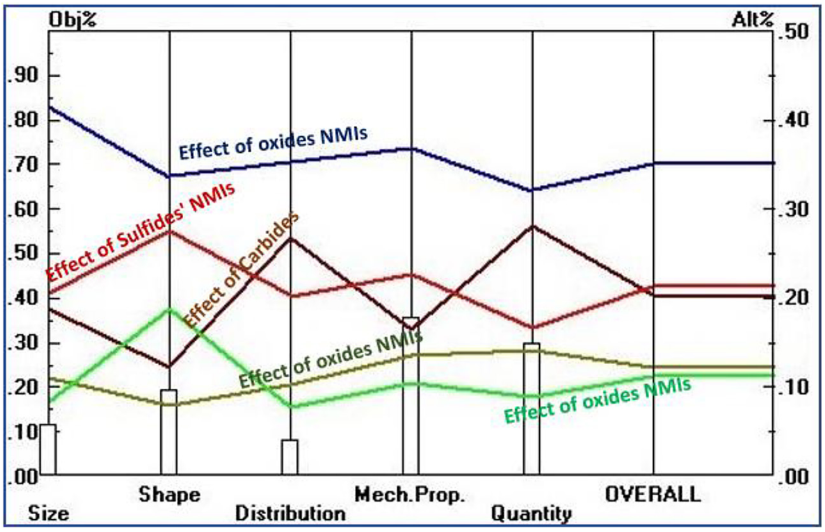

Fig. 14. Performance sensitivity results of AHP assessment

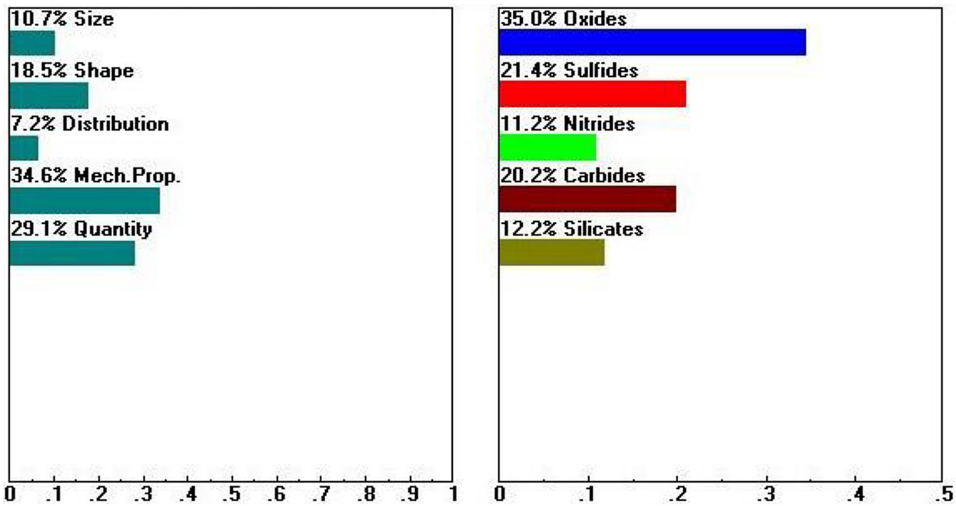

Fig. 15. Dynamic sensitivity results of AHP assessment

oxide inclusions often have a more discrete and regularly shaped morphology, which can provide less stress concentration and lower the probability of crack initiation and propagation.

CONCLUSIONS

The results achieved from the analyses of the inclusions' role led to the following conclusions:

1. The optimal type of nonmetallic inclusions in terms of fatigue cracking resistance can vary depending on the specific application and material properties in addition to shape, density, mechanical properties, and distribution of inclusions.
2. The most effective factor on fatigue resistance is the inclusion mechanical properties followed by the number of inclusion (quantity) and then the shape.
3. A spherical or globular inclusion is the best type of nonmetallic inclusion for fatigue resistance. This probably because these inclusions distributing stress more evenly and reducing the risk of crack propagation. In contrast, elongated or flat inclusions can act as stress concentrators, causing cracks to propagate more readily. Therefore, minimizing the presence of elongated or flat inclusions and increasing the proportion of spherical or globular inclusions can improve resistance to fatigue cracking.
4. Inclusions rich with oxides of calcium and aluminum, such as CaO-Al_2O_3 and Al_2O_3-SiO_2, can be beneficial in promoting fatigue resistance in steel. Spherical oxide inclusions have been shown to improve the toughness and fatigue resistance.
5. Elevated sulfide concentrations may harm the metal's characteristics, potentially instigating the promotion of cracking, embrittlement, and additional imperfections.
6. Fatigue resistance can be increased by controlling the type, size, sharpness, and number of inclusions and by insuring they are distributed evenly. It is recommended to the steel makers to reduce the other types of nonmetallic inclusions, rather than oxides, which should be kept without increasing their concentration.

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