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REVIEW PAPER

NANO-ENGINEERED STEELS: PROPERTIES AND APPLICATION

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Abstract: Steel has a dominant position among other engineering materials due to its abundance and the easiness of achieving a variety of properties with different treatments, low cost, and recycling possibilities. Today's modern engineering tends to develop new innovative materials that will have superior properties at a reasonable cost when compared to conventional steel. The development of advanced characterization methods on a small measuring scale and computational material design has increased the possibilities and interest in implementing nanotechnology in steel. Steel's microstructure can be manipulated at the nanometer scale, resulting in significant advancement in properties. Nevertheless, there are still many challenges to overcome, such as manufacturing large components of bulk nanocrystalline steel, and nanostructured steels have high strength and low ductility, making them difficult for certain applications and thus commercialization. This paper provides a review of the new emerging nanoengineered steels, with discussions on properties and potential applications. The era of nanoengineered steel has only recently begun, and its adoption is expected to accelerate in the coming years as new research findings demonstrate significant benefits.

Keywords: properties, nanoengineered steel, innovative, processing, microstructure.

1. INTRODUCTION

Steel metal alloy is the most important material on the planet, widely used in a wide range of market sectors and industries, including buildings, infrastructure, manufacturing and electrical equipment, transportation, and all types of metal products that we use every day. It is considered the most sustainable material in construction and structural engineering because it can be recycled and reused without compromising its properties, and it has the highest weight-strength ratio when compared to other construction materials [1]. However, the constant need for advancement in today's society has led researchers and engineers to implement innovative technologies for further advancement in steel weldability, and mechanical and corrosion resistance properties. In general, a good combination of properties at a low cost is preferable. Higher strength with good formability, weldability, wear, and fracture resistance sounds impossible, but nanotechnology may make it possible. Various types of properties can be obtained by manipulating metal material on a micro-scale, but with nanotechnology, changes in composition, size, and shape of structure are done on a nanoscale, opening new possibilities, and potentially resulting in completely new properties. It is also critical to understand that every advancement in the properties of steel or other construction materials will result in the use of thinner components and the reduction of natural resources, both of which are critical for protecting and preserving the environment.

Steel is used in the construction industry on bridges and buildings that are subjected to cyclic loading, which causes stress concentrations, crack initiation, and structural failure [2]. Adding copper nanoparticles to steel, according to research, reduces surface irregularities and stress risers [3][4]. This will reduce crack initiation and failure, resulting in increased safety with less monitoring and an increase in structure lifespan. When subjected to higher loading, tempered martensite steel is very sensitive to hydrogen, resulting in delayed fractures in steel bolts, limiting their strength to 1200MPa [4]. Improvements in delayed fracture problems are achieved by incorporating vanadium and molybdenum nanoparticles in high-strength bolts because the particles reduce the influence of hydrogen embrittlement and the inter-granular cementite phase [4].

Nanoparticles can improve steel's corrosion resistance, making it more durable than traditional isolations [5]. Furthermore, the addition of calcium and magnesium nanoparticles improves the heat-affected zone grains [5]. These are just a few examples of useful applications of nanoparticles on steel to give you an idea of the possibilities that nanotechnology offers. Steel research has a long history, but there are still existing problems and new demands that must be addressed. This paper summarizes current research and advancements in nanoengineered steel, with a focus on property enhancement and application.

2. NANOENGINEERED STEEL DEVELOPMENT AND PROPERTIES

The primary consideration in the design of steel structures is the selection of steel based on strength, as it is the most fundamental mechanical property, as well as the awareness of additional treatments and strengthening options. In general, a recent discovery indicates that removing imperfections or defects can significantly increase the strength of crystal materials [6]. As the volume of the material lowers, the strength of the crystals goes up, increasing the probability of avoiding defects. In fact, ultra-high strength in steel can be achieved by either narrowing crystals to the point where they are defect-free or by introducing a relatively high density of defects to form dislocation motion barriers [7].

Carbon steel wire production is an excellent example of macroscale nanoengineered steel. It is made by drawing high carbon pearlitic steel wire and subjecting it to severe plastic deformation, which multiplies dislocations and produces a dense dislocation substructure. The nano-scaled structure of cementite includes amorphous and nano-crystalline regions, as well as ferrite with a high dislocation density and supersaturated carbon atoms [8] The pearlitic wires are suitable for use in automobile tires and bridges, with a maximum strength of 4000 MPa [8]. Although the potential of nano-engineered steel is enormous and obvious, mass production of bulk nanocrystalline steel with good properties at a low cost remains difficult.

Today, there are numerous novel methods for producing nanoengineered steels. With the introduction of new analytical tools for the atomic-level characterization of steel microstructures, such as aberration-corrected scanning transmission electron microscopy (STEM) and atom probe tomography (APT), new opportunities for detailed analysis of nano-scaled precipitates, their interaction with dislocations, and the microstructural cluster of solute atoms have emerged. The design has evolved from a single type of nanoparticle precipitation to a combination of two or more types with different compositions, crystal structures, and properties, resulting in a very good combination of properties on a macroscopic level [8]. The subsequent section describes and summarizes the various processing methodologies and alloy development aspects that are currently being investigated for nanoengineered steel fabrication.

Bottom-up and top-down methods can be used to create nanoengineered metals. Bottom-up materials are assembled by agglomerating atoms and molecules using vapor deposition or fast solidification, whereas top-down materials are refined using severe plastic deformation (SPD)[9]. SPD is used in techniques such as high-pressure torsion (HPT) and equal channel angular extrusion processing (ECAP), which transform a bulk material into a new one with nanocrystalline properties. SPD techniques are excellent choices for nanoscale grain size refinement, resulting in exceptionally high strength in conventional steels and low tensile ductility [10]. There is also a method for improving workpiece properties based on surface modification by friction, which employs tools similar to those used in friction welding [9]. Thermomechanical controlled processing (TMCP) is a method of controlling the nanostructure through precipitation hardening, hot rolling, and cooling [10]. To create a thermally stable twin structure on the nanoscale, plastically strained nanoengineered steels, such as high-manganese TWIP steels, are used. If further treated for recovery or work hardening, this can result in a very good yield and tensile strength combination [10].

In addition, there is growing interest in the phase-reversion transformation approach for producing austenitic stainless-steel microstructures composed of nano and ultra-fine grains [10][11]. This method employs severe deformation to induce strain-induced transformation of austenite to martensite, which is then reverted to austenite via reversion annealing. This is accomplished through reversion diffusion or the martensitic shared reversion mechanism [11]. The nano-grained/ultra-fine structures exhibit a remarkable combination of strength and ductility [10]. The microstructure results in high yield strength and excellent elongation when deformation and phase reversion annealing are optimized [11]. Another approach to achieving martensite steel is through a computational design, in which computational models are created and used to control alloy chemistry, temperatures, cryogenic treatment, and multi-step aging for the purpose of improving the mechanical properties and corrosion resistance of steel [9],[12].

In manufacturing, there are solid-state processing techniques known as mechanical alloying and consolidation mechanical alloying that involve alloying iron and carbon powders with high-energy ball milling [9]. Some techniques also involve repeated cold welding, fracturing, and rewelding of powder particles in a high-energy ball mill [13]. According to the research in the article [13], nanocrystalline phases are produced in nearly every alloying system, grain refinement can be up to the nano-level, and materials such as nanocomposites and metallic glasses can be produced, additionally, this process can be used to synthesize some advanced materials. Combination of transformation-induced plasticity (TRIP) effect with maraging treatment in Fe- Mn base alloy system is also a methodology that is used for nano-crystallization of steel. The steels are low-carbon (below 0.02%) martensitic mix with the addition of intermetallic nanoparticles such as Ni, Ti, Al, Mo. Strength can be enhanced by the formation of nanosized precipitation, and it is important for ductility. This approach is a combination of precipitation hardening with TRIP effect providing steels with good strength and ductility at a low cost.

Surface nano-crystallization of steel is a method of producing a surface layer by subjecting the steel to surface treatment without changing its composition. A new generation of bainitic steels has also been developed using accurate phase transformation theory for bainitic reaction. At various levels, a new variant of bainitic steels known as NANOBAIN has been studied with plenty of remarkable microstructural features and properties. The ductility of nanostructured bainite is generally improved by increasing the bainitic treatment temperature, and also with moderate work-hardening and higher damage resistance, the total elongation of nanostructured bainite improves [14]. High stresses, on the other hand, cause brittle fractures of the material in samples with lower ductility long before plastic instability is predicted. In some cases, delaying the formation of the necking by increasing the incremental work-hardening rate at later stages of the uniform deformation region increases uniform elongation. Fig. 1 is an example of developed nanostructured bainite after isothermal treatment [15].

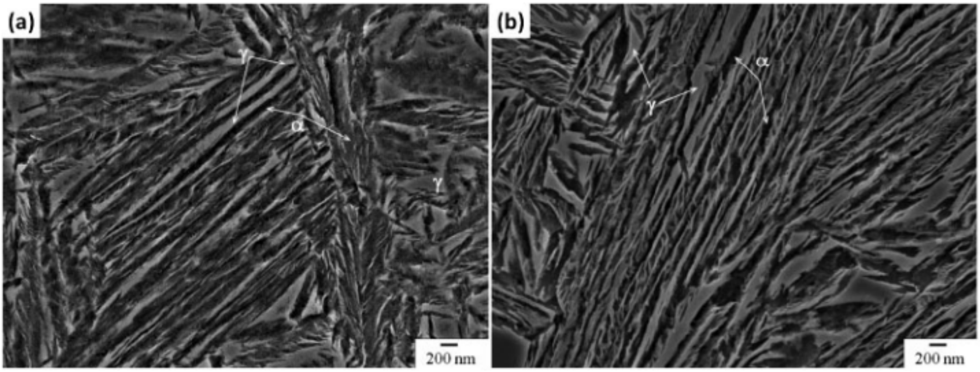

Figure 1 *Typical nanostructured bainite microstructure obtained in the 0.8C alloy after isothermal treatment at a) 220* ^{o}*C and b) 270* ^{o}*C [14].*

Triplex steels are based on Fe-Mn-C-AL with an austenitic FCC matrix and 8% ferrite and nano-sized carbides that are orderly distributed in the matrix and have high strength, formability, and energy absorption capacity [9]. Glassy ferrous alloys, which are metallic glasses that have been devitrified with heating above crystallization temperature, are also being developed [9]. These can be used in coatings as powders to increase wear and corrosion resistance [9].

3. APPLICATION OF NANOENGINEERED STEELS

Nanoengineered steel is widely used in defense (ballistic armor), aerospace (lending gears), medical (needles and clips), sports (bike frames), oil and gas (pipeline steel), nuclear (fuel cladding tubes for nuclear reactor), power (exhaust components heavy-duty diesel engines), automotive (body-structural and safety parts), industrial (cutting tools, bearings), and many other fields [9]. The interest in using nanostructured steel is at its highest point, attracting and motivating industrial companies to use the benefits of nanostructured steel through innovative approaches at an affordable price. Steel metallurgy has progressed in recent years, resulting in high yield strengths, ductility, and toughness of conventional steel, all of which are important in applications such as the automotive and aerospace industries [16]. When used in extreme conditions such as nuclear fusion power plants and space vehicles, nano-engineered steels have good mechanical properties [16].

There are several advantages and motivations for using nanoengineered steel in the transportation sector to increase strength levels. Ultra-fine grain size steels are ideal for achieving weight reduction, increased fuel efficiency, and a corresponding reduction in CO2 emissions [9]. TRIP - Maraging steels are ideal for lighter vehicles due to their improved impact resistance and formability [9]. They can also be used in anti-seismic dampers and self-adjusting turbine blades because they exhibit the shape memory effect [16]. They can provide greater radiation-induced embrittlement resistance, greater survivability in a neutron radiation environment, and higher creep strength in the nuclear industry [9]. Higher operating temperatures can improve economic performance and also result in increased safety, dependability, and lower emissions.

In the power generation, mining, cement, and concrete industries, nano-engineered steels reduce erosion, corrosion, and wear [9]. So far, experience with carbon-rich ultra-high-strength steels has resulted in brittle fractures and poor weldability due to rapid cooling. These issues do not arise in the case of nanoengineered steels strengthened by nanoscale precipitates because the carbon content is low, making them an excellent choice for additive manufacturing and re-manufacturing of complex geometries in the automotive, locomotive, and marine industries [16].

At temperatures around 500^{o}C, nanostructured steels can be used; above this temperature, precipitates grow or dissolute, and dislocations can climb over them, resulting in softening and creep deformations [16]. At cryogenic temperatures, they have low impact toughness. According to research, the right chemistry and precipitate size plays an important role in the structure and thus properties of the materials [16]. Nanoengineered steels are providing enhanced corrosion resistance for high strength and toughness steels in aerospace and the navy [9].

4. CONCLUSIONS

The development of nanoengineered steels is still in its early stages, and more research into design strategies and manufacturing techniques for production is required. There is no doubt that exceptional strength properties are possible; however, ductility requires further improvement. Furthermore, significant investments and application development are required for commercial viability to expand the application of nanoengineered steels.

This review summarizes current knowledge on the methodologies used to create nanoengineered steels, the properties obtained, and the key benefits of their use in various industries. Numerous analytical material characterization and computational techniques are being developed to better understand the complex evolution sequences from solid solution, clustering, and precipitation. Nanoscale features play an important role in controlling mechanical properties, which is why more research on strengthening mechanisms is needed.

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НАНОИНЖЕНЕРСКИ ЧЕЛИЦИ: ОСОБИНЕ И ПРИМЈЕНА

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Сажетак: Челик има доминантну позицију међу осталим инжењерским материјалима због тога што га има у изобиљу, различита својства се лако могу постићи различитим третманима, има ниску цијену и могућност рециклаже. Данашњи савремени инжењеринг тежи да развије нове иновативне материјале који ће имати супериорна својства по разумној цени, у поређењу са конвенционалним челиком. Развој напредних метода за карактеризацију у малим мјерним јединицама, као и компјутерски дизајн материјала, повећали су могућности и интересовање за имплементацију нанотехнологије у челик. Развој напредних метода за карактеризацију у малим мјерним јединицама, као и компјутерски дизајн материјала, повећали су могућности и интересовање за имплементацију нанотехнологије у челик. Микроструктуром челика може се манипулисати на наноразмери, што резултира значајним побољшањем својстава. Међутим, још увијек има много изазова које треба превазићи, као што је производња великих компоненти од нанокристалног челика, такође наноструктурирани челици имају високу чврстоћу и ниску дуктилност, што отежава њихову примену, а самим тим и комерцијализацију. Овај рад даје преглед нових наноинжењерских челика, са дискусијом о својствима и потенцијалним применама. Ера нано-произведеног челика је почела недавно, а очекује се да ће се његово усвајање убрзати у наредним годинама пошто нова истраживања показују значајне предности.

Кључне речи: својства, наноинжењерски челик, иновативност, обрада, микроструктура.