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Literature Review of Phase Transformations and Cavitation Erosion of Duplex Stainless Steels

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Abstract

Phase transformation is one of the factors that would significantly influence the ability to resist cavitation erosion of stainless steels. Due to the specific properties of duplex stainless steel, the heat treatment would bring about significant phase transformations. In this paper, we have examined the previous studies on the phase transition of stainless steel, including the literature on the classification of stainless steel, spinodal decomposition, sigma phase transformation, and cavitation erosion of double stainless steel. Through these literature investigations, the destruction of cavitation erosion on duplex stainless steel can be clearly known, and the causes of failure of duplex stainless steel in seawater can be clarified, thus providing a theoretical basis for subsequent scientific research. And the review is about to help assess the possibility of using bulk heat treatment to improve the cavitation erosion (CE) behaviour of the duplex stainless steel 7MoPLUS.

Keywords

Duplex Stainless Steel, Phase Transformation, Cavitaion Erosion

1. Introduction

The invention and use of stainless steel may be traced back to the First World War. The earliest grades made were the martensitic and the ferritic Fe-Cr grades. Then soon, the austenitic Fe-Cr-Ni steels were also invented. Nowadays, the austenitic grades have become the dominant ones in terms of amounts used and produced all over the world [1]. During the development of stainless steels, cavitation erosion (CE) has been a long-standing problem for the usage of stainless steels in various fields. For example, in the maritime industry, ship propellers are frequently rendered useless by CE. Currently, propellers are often made of the nickel-alu-minium-bronze alloys because of their good mechanical and corrosion properties. However, stainless steels have been suggested to be a better choice for resisting CE in very harsh environments. For duplex stainless steels (DSSs), one of the selling points is their good CE resistance (e.g. the S32550 DSS by Columbia Metals Ltd). In order to better investigate the phase transformation and the cavitation erosion of stainless steel, this paper will examine the previous introduction and research on this topic, which specifically includes: classification of stainless steels, two main phase transformations of duplex stainless steels, cavitation erosion and cavitation erosion of duplex stainless steels.

2. Concept and Classification of Stainless Steels

Stainless steel is stainless steel with stainless steel and corrosion resistance as the main characteristics, and the chromium content is at least 10.5%, and the carbon content is not more than 1.2%. So the Fe-Cr system is the basis of stainless steels. The minimum required amount of Cr is about 10.5 wt% for the achievement of "stainlessness". When enough Cr is added, the surface layer will change from an iron oxide to a chromium oxide. This Cr-oxide layer is adherent to the underlying metal and solid (not porous). So, it may protect the underlying metal from further oxidation. And then the resulting steel becomes "stainless" as shown in **Figure 1** [2].

Other alloying elements such as nickel, molybdenum and manganese and are added to achieve other desired properties. For instance, The Fe-Cr stainless steels have ferrite as their microstructure and they are ferromagnetic [3] [4]. For applications that cannot allow the use of magnetic materials, Ni may be added to the Fe-Cr steel. When enough Ni is present, the microstructure will change from ferrite to austenite, which is not magnetic at room temperatures [5].

In addition to Ni, Mn and N may also be used to obtain the austenite microstructure [6] [7]. Mo is typically used to get higher resistance to pitting corrosion [8], although it can also make the ferrite microstructure stable just like Cr.

Because of good properties such as high durability and esthetic appeal, stainless steels have been used extensively in many industries and applications [9]. One recent prominent application of stainless steels is their use as construction

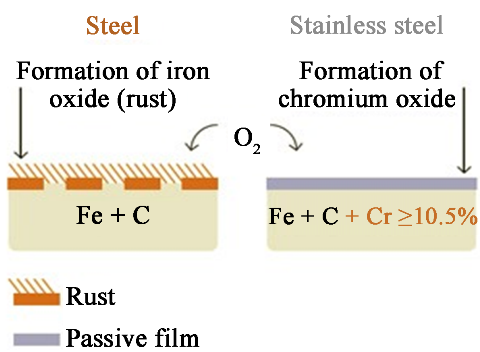


Figure 1. Formation of stainless steel [2].

materials [10] [11]. The reason for this is not only the good mechanical and corrosion properties of stainless steels, but is also the high degree of recyclability [12]. The duplex grades are finding more and more use as construction materials, as they have very high strengths and corrosion resistance [13] [14].

As mentioned above, different alloying elements are added to the Fe-Cr basis to get different desired properties. The added alloying elements may also change the microstructure, and so different types of stainless steels are obtained by changing the composition. **Figure 2** shows the broad classification of stainless steels and **Figure 3** shows how the different amounts of Cr and Ni may cause the duplex microstructure to form [15].

Special grades of stainless have been developed to have greater corrosion resistance. These are used in desalination plants, sewage plants, offshore oil rigs, harbor supports and ships propellers. Among them, the duplex grades are the usual choices for harsh applications.

3. Two Main Phase Transformations of Duplex Stainless Steels

Although duplex stainless steel has good corrosion and mechanical properties, these good properties (corrosion [18] [19] and mechanical [20] [21]) may be lost if they are exposed to elevated temperatures. This is because two main phase transformations will take place. These are spinodal decomposition under 550˚C and the formation of sigma phase between 600˚C and 950˚C. The more alloying elements are added, the faster these two transformations will occur. These two main phase transformations are shown in **Figure 4** for a similar duplex stainless steel (UNS S31803).

3.1. Spinodal Decomposition

Under 550˚C, the original ferrite decomposes into a Cr-rich ferrite and a Fe-rich ferrite. The austenite phase is not affected, however, the Fe-rich ferrite is low in Cr and so it is easily corroded [22] [23]. At the same time, the duplex stainless steel will become strengthened because the two ferrites are in nanometer scale and so they can effectively hinder dislocation movement. The ferrite regions of the Z3CN20-09M cast duplex stainless steel after annealing at 400˚C for different times. The same figure shows that the austenite phase is not changed by the

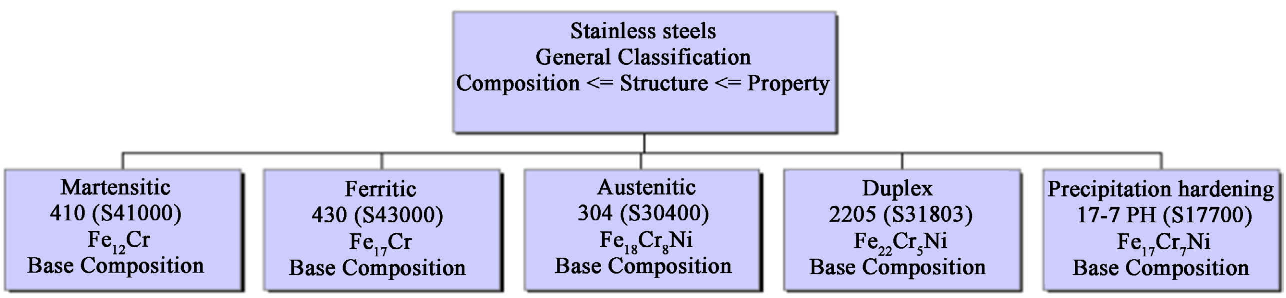


Figure 2. Classifications of stainless steels [16].

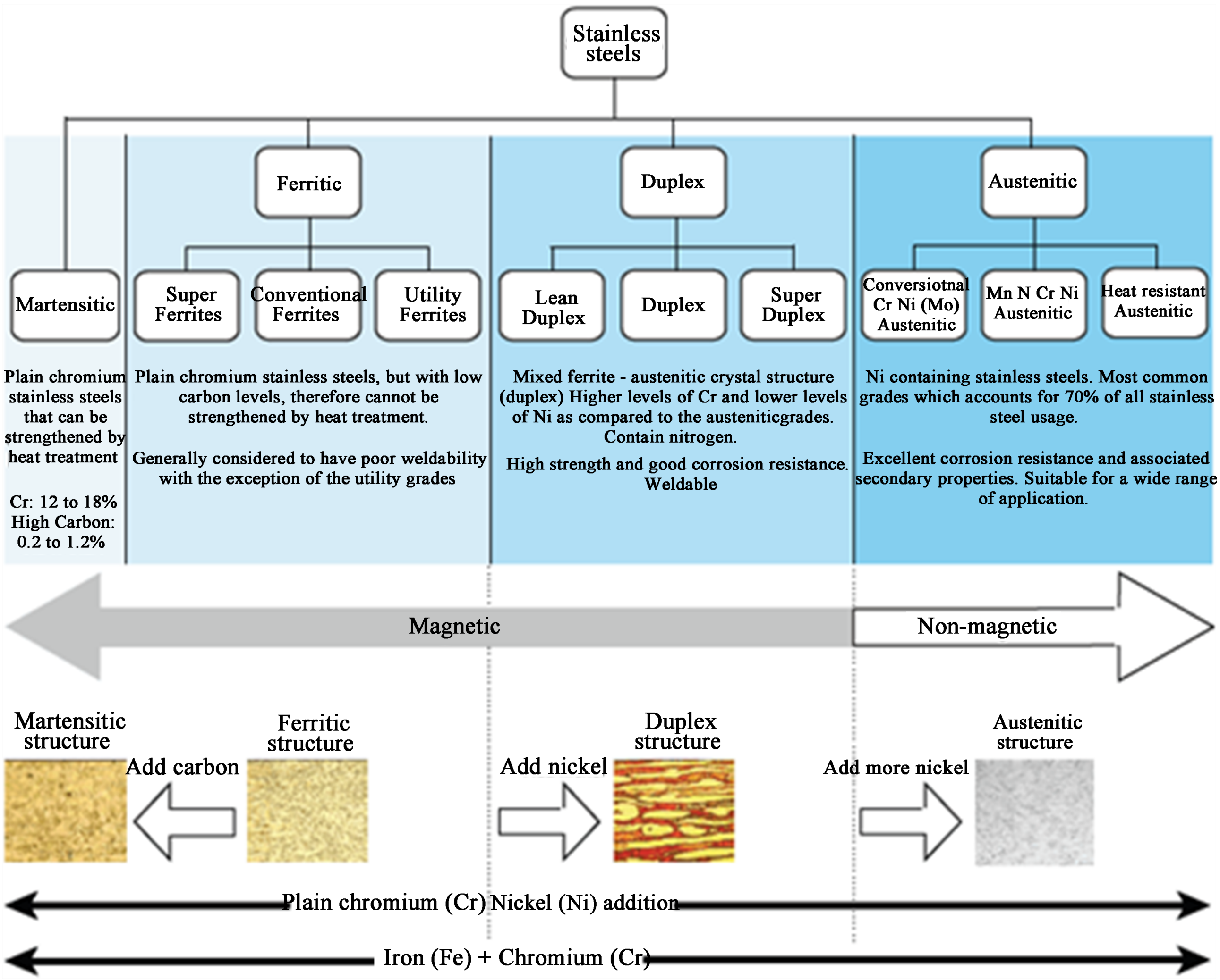


Figure 3. Effect of Cr and Ni on microstructure of stainless steels [17].

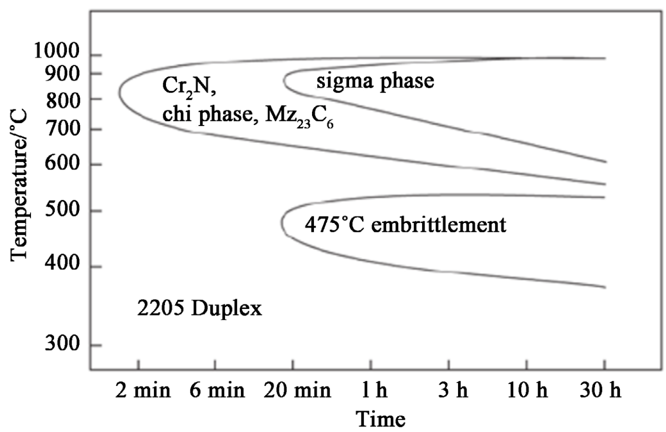


Figure 4. Precipitation-time-temperature diagram of the UNS S31803 duplex stainless steel [20].

annealing.

The decomposition of the original ferrite into the Cr-rich and the Fe-rich ferrites can occur by nucleation and growth and spinodal decomposition. The exact transformation route is affected by composition, temperature and plastic deformation [24]. Because the Cr-rich and Fe-rich ferrites are nanoscale, they are best revealed by transmission electron microscopy (TEM). The mottled contract of the ferrite after spinodal decomposition of a grade 2205 duplex stainless steel is shown in **Figure 5**.

Usually, when spinodal decomposition occurs, inside the ferrite regions, the G phase will also form. Because the G phase shows in small amounts, its effects on properties of duplex stainless steels are believed to be small also. However, recent studies have found this view may not be true [26]. Some researchers have stated that the G phase would contribute significantly to hardening [26]. The G phase is usually very small in size, which is shown in **Figure 6** for a duplex

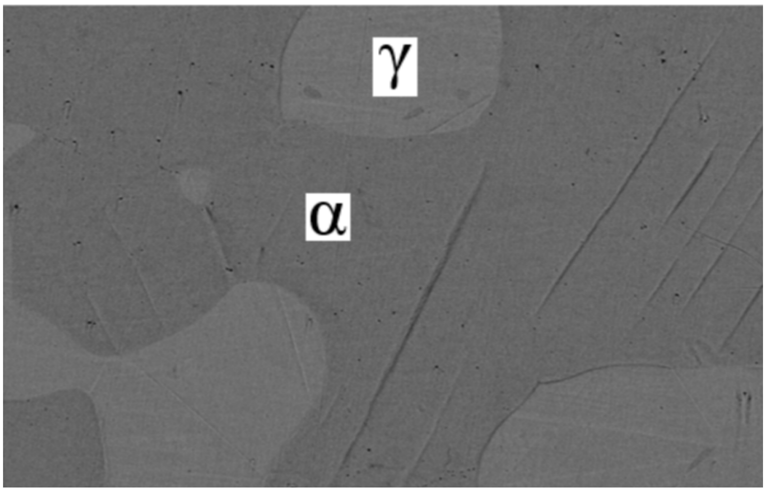


Figure 5. The ferrite and austenite of a grade 2205 duplex stainless steel after spinodal decomposition treatment [25].

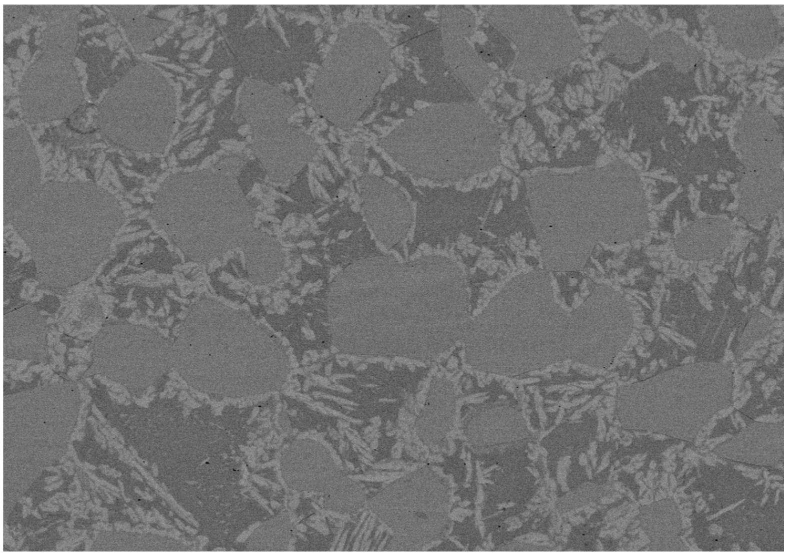


Figure 6. G phase of the Z3CN20-09M duplex stainless steel after annealing at 400˚C for 10,000 h [27].

stainless steel after it is annealed at 400˚C for 10,000 h.

3.2. Sigma Phase

The intermetallic sigma phase of duplex stainless steel usually forms between 600˚C and 950˚C, but may sometimes form up to almost 1000˚C. The sigma phase contains a lot of Cr and Mo. A simple parameter for estimating the formation of sigma phase is given by the sigma equivalent number:

$$\sigma_{eq} = \%Cr + 4.5\%Mo + 1.5\%Si$$

The sigma phase can make duplex stainless steels to become stronger (but hard and brittle). Also, corrosion resistance may be decrease because the matrix may lose a lot of Cr and Mo to the sigma phase. In **Figure 7**, it may be seen that the sigma phase is embrittling but strengthening. The sigma phase may also affect other mechanical properties in a bad way such as.

As the sigma phase increases in volume, the degree of Cr depletion of the matrix increases too. This depletion is given by the horizontal axis of **Figure 8** in terms of the degree of sensitization (DOS). This causes the resistance to pitting as reflected by the pitting potential to keep decreasing.

In duplex stainless steels, the chi phase usually forms in a similar temperature range as the sigma phase. Usually, the chi phase forms before the sigma phase forms. This phase contains a lot of Mo and may also cause embrittlement and decrease of corrosion resistance as the sigma phase [28] [29] [30].

In **Figure 8**, it is seen that both the chi phase and the $M_{23}C_6$ carbide form before sigma phase. Some researchers have found that the chi phase and the $M_{23}C_6$ carbide may transform into the sigma phase as the annealing proceeds [20] [31].

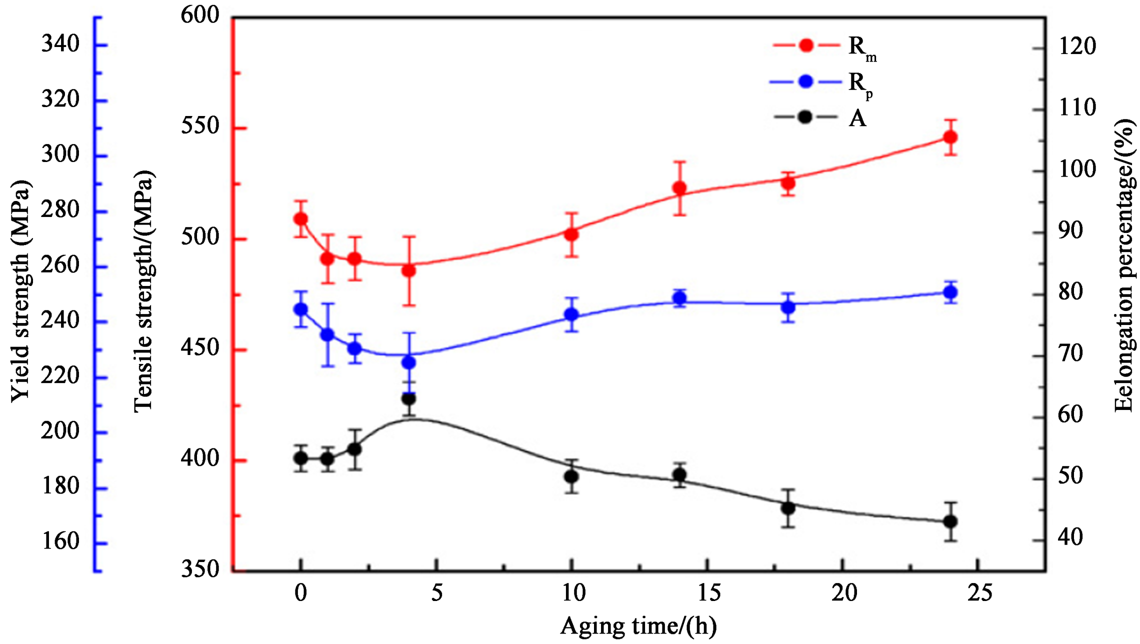


Figure 7. The strengthening and embrittlement caused by the formation of sigma phase in the Z3CN20.09M duplex stainless steel [27].

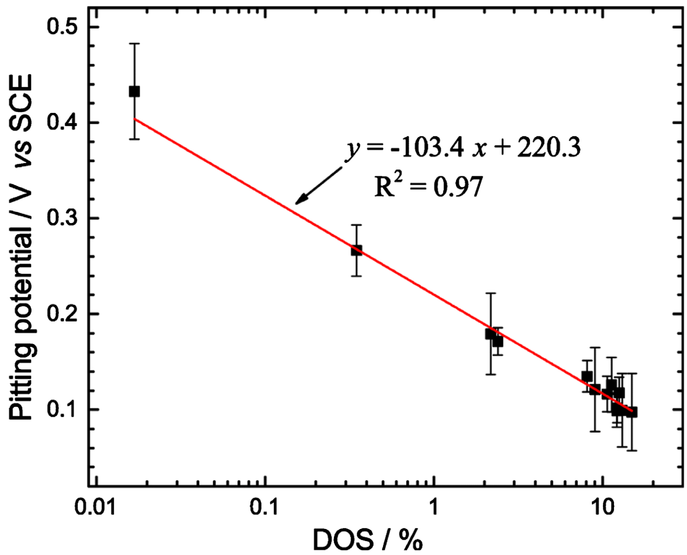


Figure 8. Reductions in pitting potential and critical pitting temperature due to the precipitation of the σ phase [28].

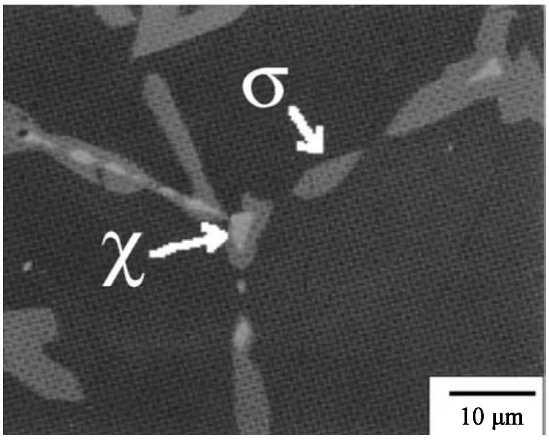


Figure 9. Co-existence of the χ phase and the sigma phase [31].

The co-existence of the sigma phase and the chi phase and the $M_{23}C_6$ carbide are shown in Figure 9 and Figure 10.

4. Cavitation Erosion

Cavitation occurs when a liquid phase changes into a gas phase. The phase diagram of water in Figure 11 shows that both the temperature and pressure may cause a liquid-to-vapor phase change. The cavitation referred to in this paper means the occurrence of cavitation caused by a pressure drop (indicated by the arrow in Figure 11).

In Figure 12(a), the pressure and velocity will change from location to location on a flow line. If the pressure at location A is lower than the vapor pressure of the fluid, the fluid will change into a gas. Figure 12(b) is a real example of a hydraulic component affected by the cavitation phenomenon.

The cavitating bubbles shown in Figure 12(b) collapse after short time after

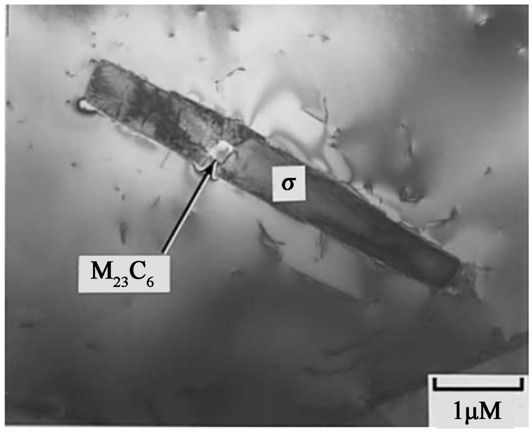


Figure 10. Co-existence of the $M_{23}C_6$ carbide and the sigma phase [20].

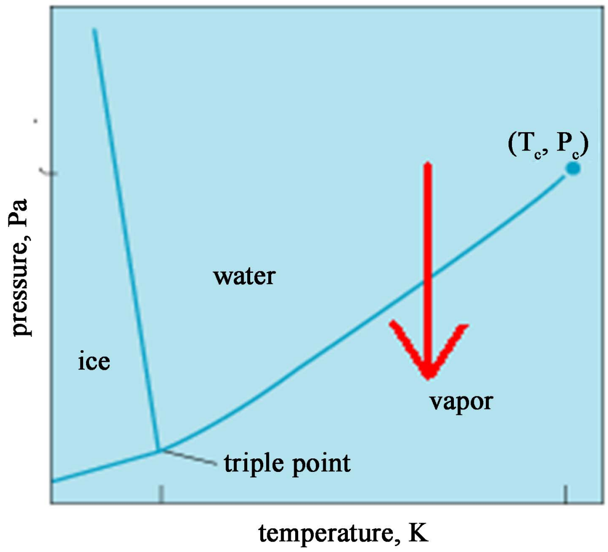
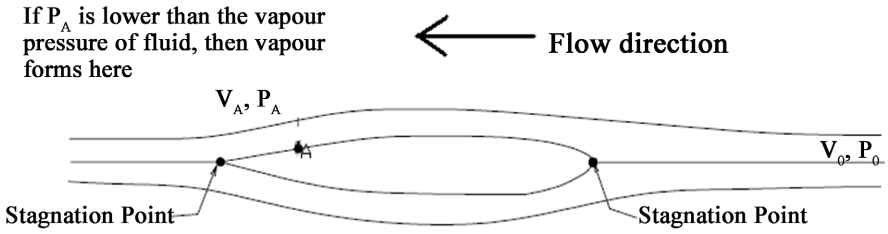


Figure 11. The phase diagram of water [32].

they are generated. When they collapse, they may produce shock waves that can induce stresses higher than 1000 MPa in the surface of the solid. This high stress level can easily damage common engineering metals. Hence, many hydraulic components are failed by the erosion caused by cavitation, these include ship rudders and fan blades in hydraulic valves.

5. Cavitation Erosion of Duplex Stainless Steels

Over the years, the cavitation erosion behaviors of many engineering metals have been studied. These include conventional grades of stainless steels, copper and its alloys, aluminum and its alloys. Duplex stainless steels are also studied by many people. One situation for cavitation erosion of duplex stainless steels to be a problem is in desalination plants. Many components such as valves and pipes of a desalination plant are operated with flowing seawater. In the reverse osmosis process, highly corrosive flowing seawater is seen. Currently, the superaustenitic stainless steels (e.g. the 6Mo series) and Ni-based alloys are used. However,



(a)

(b)

Figure 12. (a) Schematic describes flow over an object [33], (b) Cavitation on a propeller [34].

more of these components are being replaced with duplex stainless steels because nickel is expensive [35] [36] [37] [38].

It must be emphasized that even though the typical operating temperature range of the pipes and valves handling seawater in some desalination plants is about 120˚C, which may not be high enough to cause corrosion problems due to spinodal decomposition and sigma-phase formation, the fabrication of the components typically involve welding operations. The neighborhoods of the welded parts may contain sigma phase or undergo spinodal decomposition. These regions are particularly weak against corrosion, and corrosion may make cavitation erosion more serious [39] [40].

6. Conclusion

The cavitation erosion resistance of solution-treated duplex stainless steels is not high and this has limited their uses as hydraulic components. By examining the previous research and their results, this paper will be able to serve as the guideline and framework for investigating whether spinodal decomposition and sigma phase formation can be used for the improvement of the cavitation erosion resistance of duplex stainless steels. The improvement of the anti-cavitation erosion ability of duplex stainless steel will greatly improve the service life and reliability of marine equipment such as ships. In this paper, the phase transformation mechanism and corrosion resistance of duplex stainless steel are reviewed, which lays a solid foundation for the later heat treatment and laser treatment of stainless steel in the future.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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