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Review Article

EFFECT OF DEFORMATION ON CORROSION BEHAVIOR OF AUSTENITIC STAINLESS STEEL: A REVIEW

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ABSTRACT

This review summarizes the effect of plastic deformation on the corrosion behavior of austenitic stainless steel. The austenitic stainless steels are used in boilers, nuclear reactors, and chemical reactors, due to their excellent corrosion resistance and mechanical properties. Plastic deformation and the precipitation behavior of the steels at elevated temperature would lead to the deterioration of corrosion resistance and mechanical properties, it is essential to clarify the effect of plastic deformation and secondary phases on the mechanical properties and corrosion resistance of the steels. Here, a summary of recent progress in the effect of deformation on microstructure and corrosion in austenitic steels is made. Secondary phases, like $M_{23}C_6$, MX and sigma phase are formed under high temperature application; they are harmful phases in austenitic stainless steels. Cold forging has a great influence on the corrosion behavior of austenitic stainless steels. The Stress Corrosion Cracking (SCC) susceptibility of the cold forged austenitic stainless steels increases with increasing the extent of cold forging, but hot forging improve the SCC and pitting corrosion resistance of austenitic stainless steel. Plastic deformation also improves the strength and hardness of stainless steel.

INTRODUCTION

The austenitic stainless steels are used in boilers, nuclear reactors, and chemical reactors, due to their excellent corrosion resistance and mechanical properties (S.J. Zinkle *et al*., 2013). Stress corrosion cracking might occur during the long-term service at high temperature in stainless steel. Especially, SCC behavior of austenitic stainless steels has become a major problem in the oil and nuclear industry (T. Allen *et al*., 2010). Pitting and carbide precipitation is the major cause off SCC initiation time and crack growth rates (CGR) in components made of austenitic stainless steels in boiling water reactor (BWR) in oil and nuclear plants. (Ilevbare *et al*., 2011) reported that the boiling water reactor component failures were associated with cold work. SCC susceptibility in Cold worked austenitic stainless steels is much higher than the solution annealed steel (M.F. McGuire *et al*., 2008). This paper presents an overview of effect of plastic deformation, precipitation and the coarsening of different carbides in austenitic stainless steels. The hot forging of austenitic stainless steels which play a major role in controlling the microstructures and mechanical properties of the steels will also be discussed. The Stress Corrosion Cracking (SCC) susceptibility of the cold forged austenitic stainless steels increases with increasing the extent of cold forging, but hot forging improve the SCC and pitting corrosion resistance of austenitic stainless steel. Plastic deformation also improves the strength and hardness of stainless steel(P.L. Andresen *et al*., 2001).

Table 1 Typical chemical composition of austenitic stainless steels (in wt.%)

Steels	Fe	C	Cr	Mn	N	Mo	S	P	Ni
316L	Bal.	0.03	20	2	0.10	3	0.030	0.045	14
304L	Bal.	0.03	20	2	0.10	-	0.030	0.045	12
316	Bal.	0.08	18	2	0.10	3	0.030	0.045	14
304	Bal.	0.08	18	2	0.10	-	0.30	0.045	12

Effect of Cold Deformation in Austenitic Stainless Steel

Cold-deformation introduces deformation twins, dislocations and residual stresses, cold forging increase the hardness and strength of steels, accompanied by reduced ductility. Cold deformation increases the susceptibility of SCC in stainless steels. (Feron *et al*., 2005) investigate that the SCC susceptibility of the cold forged stainless steels increases with increasing the extent of cold deformation. (García *et al*., 2009) reported that SCC of the cold-worked 304 stainless steels is caused by increasing the % of cold deformation. Perez *et al*. also reported that the SCC in the cold-rolled 316 stainless steels

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is accomplished by the deformation twins formed during cold rolling. For improving the strength and fatigue resistance of the nuclear reactor components, they are usually subjected to cold-working (F.P. Ford *et al*., 1994). Deformation twins and dislocation are major defects in cold forged austenitic stainless steels. The effect of deformation twins caused by cold deformation on SCC behavior of the austenitic stainless steel has rarely been reported. Therefore, SCC susceptibility of the cold deformed stainless steels needs to be evaluated. The SSRT test provides the useful information on SCC behavior of materials; it also provides the short experimental time to evaluate SCC susceptibility of material. Generally cold deformation increases the SCC susceptibility in austenitic stainless steel (Z.P. Lu *et al*., 2008).

Effect of Hot Deformation in Austenitic Stainless Steel

Over the past decades, a great number of researchers of austenitic steels have been made on corrosion behavior and microstructure evolution at high temperatures application, whereas little attention has paid to the hot deformation performance of the austenitic stainless steels at high temperature. In fact, the hot deformation processing maps are essential for optimizing the mechanical properties and control the microstructures of the stainless steel. (Farahat *et al*., 2009) reported that hot forging produced smaller grains with thinner carbide surrounding the grains boundary in austenitic stainless steels. Guo *et al*. concluded that the lower strain rate and higher deformation temperature would produce the smaller grain in 316L austenitic steel. Dynamic recrystallization (DRX) occurs during the hot forging of stainless steel at high temperature. However, recrystallized grains can be deformed since strain softening and strain hardening take place above the recrystallization temperature, during solution anneal treatment resulting the formation of annealing twins in stainless steel. However, a few deformed grains recrystallized in steel below the recrystallization temperature, with stress relief heat treatment 16. In conclusion, effects of hot forging on the corrosion are concluded as: (1) Smaller grain size; (2) more CSL boundaries in steel; (3) higher the residual strain. Compared with samples in stress relief treatment after forging, samples with solution anneal treatment contain higher residual strain.

Effects of Heat Treatments on the Oxidation Behavior of Austenitic Stainless Steel

Degradation of metals depends on the microstructural characteristics and residual strain. The review in this paper suggests that the steel with solution anneal heat treatment contain much more CSL boundaries than the other stress relive heat treatment. More CSL boundary is caused by the long holding time during solution anneal heat treatment, formation of much more deformed grains recrystallizing during the process (R. Kilian *et al*., 2007). Formation of equiaxed grains and strain free grains due to recrystallization are responsible for the development of residual strain. The residual strain is lower in solution anneal heat treated steel. Decrease in the dislocation density and residual strain after solution anneals treatment in steel is due to recrystallization of deformed grains. Therefore, it can be concluded that the oxide film is more protective in solution anneal treated 316LNss after forging as compared to that grown on samples with stress relief treatment and that grown on as-received samples without forging (Z. Shen *et al*., 2014).

Precipitation Behaviors of Austenitic Stainless Steel During Heat Treatment

Austenitic stainless steels can be strengthened through solution hardening, precipitation hardening, and dispersion hardening. Nano-size fine precipitates in matrix would improve the creep strength and corrosion resistance of the materials. Isothermal heat treatment at temperatures above 500^{o}C can promote the precipitation of carbide and secondary phases that alter the corrosion resistance and mechanical properties of steel (N. Matsubara *et al*., 2011). Therefore, the mechanism of formation of carbide and secondary phases has to be recognized and understood. The austenitic stainless steel microstructure is characterized by MX carbide dispersed in the austenitic matrix. In some cases, certain amount of $M_{23}C_6$ (M = Cr) phase may be present in steel when heat treated for long time, especially for those steels with high content of chromium. M_7C_3 carbides are also found in stainless steel. Generally, nano-size block-shaped MX carbonitridesare nucleated and precipitate at grain boundary, whose size is increased with the increasing heat treatment temperature. The formation of MX carbonitrides has been investigated by annealing at temperatures above 500^{o}C, and MX carbides are identified as intergranular corrosion with an FCC crystal structure. The precipitation of these carbides would lead to the restriction of dislocation movements and then improve the corrosion resistance and creep strengthat high temperatures application of steel. Stabilizing alloying components like Ti, Nb, and V have a higher affinity to carbon than chromium, which is beneficial to the formation of MX carbides. Thus, strong carbide forming alloying elements are usually introduced to restrict the formation of $M_{23}C_6$ carbides. Higher N content can also contribute to the formation of MX carbides. Above all, MX carbonitrides are the predominant precipitates for the strengthening of austenitic steels.

CONCLUSIONS

In this review paper, effect of deformation on corrosion, mechanical properties and the behaviour of precipitates during high temperatures heat treatment in austenitic steels are discussed. The second phase such as MX carbonitrides, $M_{23}C_6$ carbides, Z phase, sigma phases are all studied. Due to the thermal stability of MX carbonitrides, they are beneficial for the improvement of the strength of the steels. While, it is hard to acknowledge that whether the phases like $M_{23}C_6$, sigma phases would be favorable to the steels. Since $M_{23}C_6$ carbides are easy to nucleate and grow fast along grain boundaries, they are harmful phases in austenitic steels. Sigma and Laves phases are brittle phases that are detrimental to the performance. The majority of the detrimental phases like $M_{23}C_{6,}$MX and Sigma phases tend to coarsen during service. The best way to improve the properties of austenitic stainless steels is to control the size, distribution, shape of the secondary phases. The hot deformation behavior of austenitic steels is reviewed. By adopting proper hot deformation, the microstructure and performance of the stainless steels can be further improved. Cold forging has a great influence on the corrosion behavior of austenitic stainless steels. The Stress Corrosion Cracking (SCC) susceptibility of the cold forged austenitic stainless steels increases with increasing the extent of cold forging, but hot forging improve the SCC and pitting corrosion resistance of austenitic stainless steel. Plastic deformation also improves the strength and hardness of stainless steel.

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