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Effect of nitrogen and cold working on structural and mechanical behavior of Ni-free nitrogen containing austenitic stainless steels for biomedical applications

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ABSTRACT

This investigation deals with the evaluation of structural and mechanical behavior of deformed (10% and 20% cold work) and annealed (at 1050 °C for 15 min followed by water quenching) Ni-free high nitrogen austenitic stainless steels (HNSs). The microstructure was observed by optical micrograph and the mechanical properties were determined by macrohardness and tensile tests. Both stress strain behavior and work hardening behavior were evaluated. HNSs have smaller grain size as compared to low nitrogen steels and no formation of martensite was observed after 20% cold working. Further, it was found that hardness; yield strength and ultimate tensile strength of the steels linearly increases and elongation decreased with nitrogen content and degree of cold working. The strength coefficient was observed to be higher for the high nitrogen steels; it decreased to some extent with degree of cold working. The work hardening exponent was also observed to decrease with degree of cold working. Influence of nitrogen on mechanical properties was mainly related to its effect on solid solution strengthening. X-ray diffraction analysis of annealed as well as deformed alloys further confirmed no evidence for formation of martensite or any other secondary phases. SEM fractography of the annealed and deformed samples after tensile tests indicates predominantly ductile fracture in all specimens.

1. Introduction

Metals and alloys have been widely used in various forms as implants, which provide the required mechanical strength and reasonable corrosion resistance. The mechanical properties decide the type of material that will be selected for a specific application. Some of the properties that are of prime importance are hardness, tensile strength, modulus and elongation. Stainless steels (e.g. 316L) is a representative of metallic biomaterials and is widely used in orthopedic implants, with the main advantages of easy processing, good mechanical properties, good corrosion resistance, adequate biocompatibility and very low cost [1,2]. Due to the cost of nickel and to prospected possibility of allergic reactions in the human body, nickel-free high nitrogen austenitic stainless steels (SSs) are highly attractive for medical applications. Nitrogen-alloyed high manganese austenitic steels with better combination of strength, toughness, corrosion resistance, and nonmagnetic, are considered to be good substitute for the traditional Cr–Ni stainless steels and being widely used as orthopedic implants [3].

Nitrogen is known to be a strong austenite stabilizer. It is well established that interstitial nitrogen has the greatest solid-solution strengthening effect [4–6] which consequently causes an increase in the high strength of stainless steels without effecting their good ductility and toughness properties [7] as long as solubility limit of nitrogen in austenitic is not exceeded. Additionally, nitrogen stabilizes so strongly the austenitic phase, that nitrogen alloyed austenitic stainless steels can be work hardened to very high strength levels without strain induced martensite formation [8]. Yield and ultimate tensile strengths of austenitic stainless steels increase linearly at room temperature with increase interstitial nitrogen content, due to solid solution hardening and grain boundary hardening [9].

A recently developed P558 alloy has a high Mn and N content and a negligible Ni (≤0.20%), is more resistant against dry wear, and shows very high strength and hardness, in solution annealed and cold worked condition [10]. Carpenter Technology Corporation reported a HNS, BioDur 108 (Fe–23Mn–23Cr–1Mo–0.9N) [11–13], which can be considered as an alternative to the common austenitic stainless steels. The yield strength of BioDur 108 alloy is approximately 606 MPa (88 ksi) in the annealed condition. In comparison, typical yield strength of 316L is approximately 241 MPa (35 ksi). Büscher and Fischer et al. [14] from Germany studied the mechanical, chemical and tribological properties of nickel-free austenitic steel, P2000 (Fe–18Cr14Mn–3Mo–(0.75–1.0) N). This steel showed enormously high strength, high ductility and superior corrosion resistance. Yang and co-workers from the Institute of Metal Research, CAS, developed a new HNS (BIOSSN4) for medical application [15–19], with nominal composition of Fe–18Cr–

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Table 1
Composition of stainless steels (wt.%).

Sample	C	Cr	Mn	Ni	Si	Mo	S	P	N	Fe
316L	0.02	17.19	1.56	14.0	0.71	2.77	0.004	0.015	0.06	Bal.
316LVM	0.02	17.24	1.68	14.42	0.24	2.83	0.004	0.007	0.07	Bal.
$316MnN_1$	0.48	19.32	12.77	0.05	0.26	3.32	0.006	0.009	0.34	Bal.
$316MnN_2$	0.08	19.11	11.85	0.08	0.25	3.02	0.004	0.010	0.43	Bal.
$316MnN_3$	0.017	18.28	11.92	0.04	0.07	3.24	0.003	0.008	0.52	Bal.

15Mn–2Mo–(0.45–0.7) N. This steel has excellent combination of strength and toughness, sufficient fatigue strength; good wear resistance, better corrosion resistance and promising biocompatibility, compared with the 316L. Both yield strength and ultimate strength of BIOSSN4 steel are far higher than those of 316L steel.

Many studies related have been performed on the effect of cold working on structural and mechanical behavior of stainless steels. Bhav Singh et al. [20] have reported that increased percentage of cold reduction increases the strength and hardness with loss of ductility and decreases the energy absorption of nitrogen alloyed austenitic stainless steels. Strain-induced α′-martensite produced in metastable austenitic stainless steels during cold rolling led to significant increase in their strength. The formation and the amount of strain-induced martensite depend on the austenite stability (chemical composition and initial austenite grain size) and the rolling conditions (the deformation amount and temperature, and rolling speed). When the austenite stability and the deformation temperature are low, or the amount of deformation is high, the martensite content will be increased [21].

In our previous work, the nickel free high nitrogen austenitic stainless steels have been prepared using induction furnace. The Fe-Cr-Mn-Mo-N series high nitrogen austenitic stainless steels with different nitrogen contents have been developed and their biocompatibility and corrosion behavior have been evaluated. It was found that they possess excellent biocompatibility and their corrosion resistance was very high as compared to 316L and 316LVM stainless steels [22,23]. It was also studied in our previous work that biocompatibility and corrosion resistance increase to some extent with cold working in these Ni-free steels. In the present work, the structural and mechanical properties of these high nitrogen austenitic stainless steels were investigated using optical micrograph, macrohardness and tensile testing. Both stress strain behavior and work hardening behavior were evaluated. X-ray diffraction (XRD) analysis of the samples was also carried out. SEM fractography analysis of the annealed and deformed samples after tensile test was also carried out.

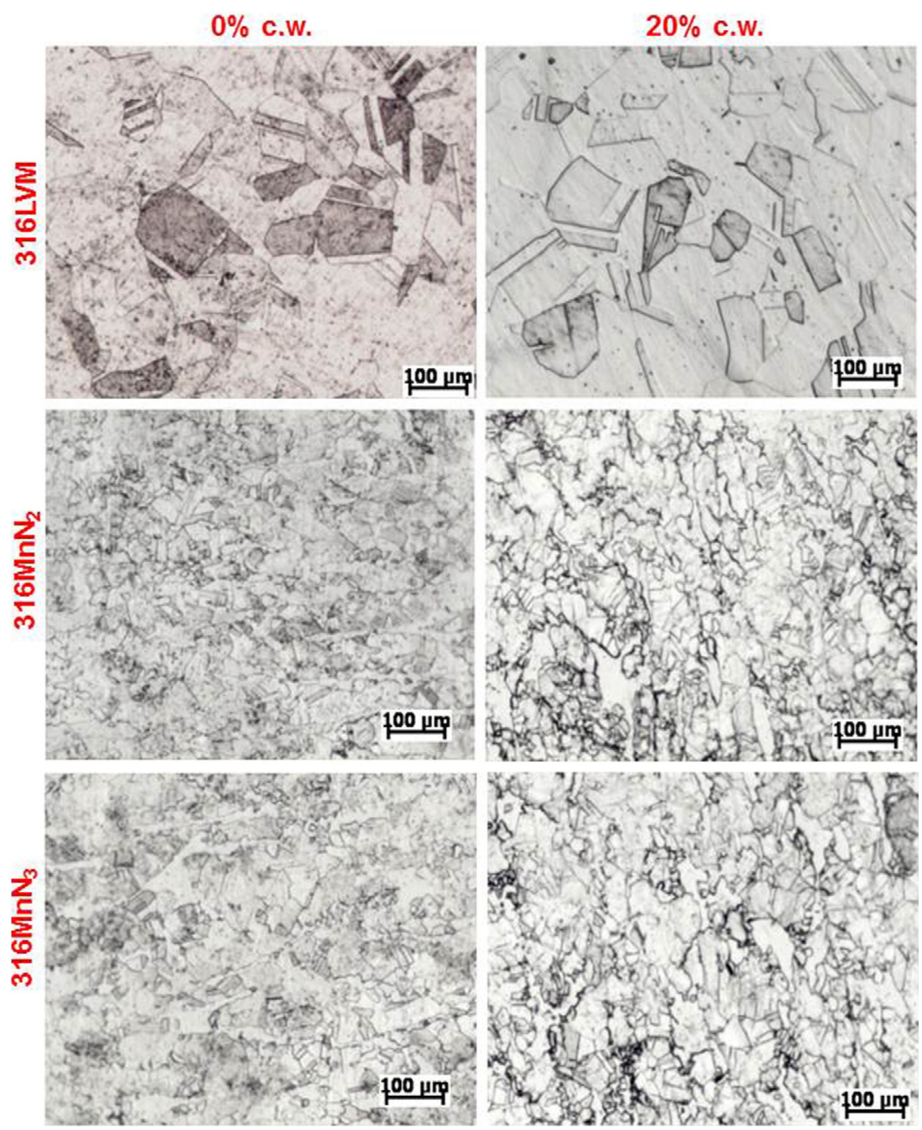

Fig. 1. Optical micrographs of different stainless steels in annealed and 20% cold worked condition.