PROPERTIES OF 17 – 4 PH STAINLESS STEEL PRODUCED VIA PRESS AND SINTER ROUTE

Prasan K. Samal, Nagarjuna Nandivada
North American Hoganas
and
Ingrid Hauer, Hoganas AB

ABSTRACT

Ferritic and austenitic stainless steels exhibit moderate levels of strength which are adequate for a wide range of applications. Martensitic stainless steels offer significantly higher strengths, but have very low ductility. For applications requiring high levels of strength (typically, above 600 MPa, 87 KSI in tensile strength) and a moderate ductility, alloys from the precipitation strengthened family of stainless steels are often considered as potential candidates. The most popular alloy of this family is 17-4 PH. Full dense version of this alloy, produced via MIM route, has gained a high degree of acceptance in many demanding applications.

Conventional PM processing of 17-4 PH poses a number of challenges, the primary one being the achievement of a near-full theoretical density. This paper describes the optimum processing parameters, and properties of the alloy in both as-sintered and heat treated conditions. The effects of process parameters and the residual carbon content on the microstructure and mechanical properties are examined.

INTRODUCTION

Precipitation hardening (PH) grades of stainless steel offer significantly higher strengths in comparison to the austenitic and ferritic grades of stainless steel. The PH grades are also superior to most martensitic grades of stainless steel in terms of strength, ductility, and corrosion resistance. In ingot metallurgy (IM), PH grades offer an advantage with formability, since these alloys can be cold formed to the finished shape of the component while in a ductile state, and then heat treated to maximize strength and hardness. In IM, the alloy 17-4 PH is the most popular grade among the PH family of stainless steels. It is also one of the most widely used materials in the metal injection molding (MIM) industry.

In both IM and MIM, the popularity of 17-4 PH stems from its unique combination of high strength, moderate ductility, and good corrosion resistance. Although its corrosion resistance is not at par with those of most austenitic grades of stainless steels, when compared to the high strength martensitic grades,

the 17-4 PH alloy exhibits superior corrosion resistance due to its higher chromium and nickel content. This grade of stainless steel is classified as a martensitic precipitation hardening alloy, based on the fact that its matrix always remains martensitic at room temperature. Achievement of optimum strength and ductility requires specific heat treatment schedules designed to produce sub-microscopic precipitates uniformly throughout the matrix. These precipitates further strengthen the martensitic matrix without severely lowering its ductility. The heat treatment schedule comprises a solution annealing step at a temperature high enough to stabilize the austenitic matrix. The precipitate forming elements are highly soluble in the austenite phase and, hence, are held in solution during the solution annealing step. Quenching of the alloy from the austenitizing temperature to room temperature effectively retains these precipitate forming elements in super saturation in the martensitic matrix. Upon heating the alloy to some intermediate temperature and holding at that temperature for several hours (called aging), very fine, second-phase particles precipitate from the supersaturated, martensitic matrix. The aging temperature and time period determines the growth rate, hence the final size and distribution of the precipitates. The alloys high strength results from both its martensitic matrix and the strain induced into the crystal lattice by the presence of the fine precipitates. With a low carbon content of less than 0.07%, the martensitic matrix that forms in this alloy is of the low carbon (lath martensite) type, and it is relatively more ductile than the high carbon based acicular martensite. Typically, the highest strength is achieved when the precipitates are smaller than the size that can be identifiable under an optical microscope. Typically, the IM processed 17-4 PH alloys offers tensile strengths ranging from of 1000 to 1300 MPa (145 to 189 KSI), with elongations in the range of 8 to 15%.The MIM processed 17-4 PH alloy typically exhibits tensile strength ranging from 800 to 1200 MPa (115 to 172 KSI), with elongations ranging from 5 to 10%.

Press and sinter PM process has not been considered as an acceptable method for component manufacture from 17-4PH alloy, primarily because of its inability to produce parts with full or near-full theoretical sintered densities. Typically, a commercial single-press-single-sinter PM process can produce components having a sintered density in the range of 6.8 to 7.3 g/cm^3, for most of the common grades of stainless steel. Within this range, a higher density is achieved by compacting at a relatively high pressure, followed by sintering at a relatively high temperature (e.g., > 1288 ^{0}C, 2350^{0}F). In this respect, the inherent high hardness of the atomized 17-4 PH powder poses as a significant hurdle to achieving high sintered densities. Efforts by earlier researchers have been aimed at enhancing the sintered density of 17-4 PH, in addition to developing process parameters for maximizing mechanical properties of the alloy via the PM route. Reinshagen and Witsberger [1] have demonstrated that it is feasible to achieve a sintered density of 7.30 g/cm^3 by utilizing powders with a higher than normal fines (< 45 micrometers) content. Heat treated (aged at 482^{0}C, 1025^{0}F, or H900) samples in their study exhibited an ultimate tensile strength (UTS) of 1080 MPa (157 KSI), combined with a 4.2% tensile elongation. In their study, as-sintered parts were directly aged without a solution annealing treatment. Schade, et al. have demonstrated that by keeping interstitial contents (carbon and nitrogen) of the alloy powder at low levels, it is possible to achieve higher than normal green and sintered densities under commercial compacting and sintering conditions [2]. However, the strength and ductility levels achieved in their study were significantly lower than those obtained by Reinshagen and Witsberger, with H900 tensile strength of 773 MPa (112 KSI) and an elongation of 1.5%. The solution annealing step was also bypassed in the Schade, et al. study.

Despite the fact that a PM processed 17-4 PH would have significantly lower ductility in comparison to its IM or MIM counterparts, it may still be a desirable material if it can fill the property gap that does exist between the austenitic and martensitic grades of PM stainless steels. Currently, the martensitic 410 and 420 grades of stainless steel are the only options that one has for producing high strength PM stainless steels via single-press-single-sinter route. Although it is feasible to achieve ultimate tensile strengths in the vicinity of 800 MPa (140 KSI), these materials are extremely brittle, exhibiting tensile elongations of less than 1.0% (Table 1). The low ductility of these PM martensitic materials limits their

usage to applications such as wear plates and bushings, mainly. It is anticipated that if a single-press-single-sinter version of 17-4 PH alloy can offer tensile strengths that are higher than those exhibited by alloy 420, along with 3 to 4 % tensile elongation, then the requirements of many other high strength applications can be met by PM. It is also anticipated that PM 17-4 PH would exhibit higher corrosion resistance when compared to PM 420, owing to its higher chromium and nickel contents.

To the authors' knowledge, only limited efforts have been made by parts fabricators to process 17-4 PH alloy via the press and sinter route, and also that wide variations are seen in the mechanical properties obtained with seemingly well controlled process parameters (the large differences seen between the data presented in the above two papers serve as examples). It is reported that wide inconsistencies exist in the mechanical properties, between the parts made in the same sintering run, as well as from one sintering run to another -- especially when parts are tested in the as-sintered condition. Preliminary evaluations carried out by the authors led them to believe that the inconsistencies are primarily due to the high sensitivity of the alloy to the cooling rate (from the sintering temperature) and also to differences in the residual carbon content in the material.

Table 1: Strength and ductility levels offered by selected PM stainless steels [3, 4]

Alloy	Carbon addition	Metallurgical condition	Sintering temp.	Sintering atmo.	Sintered density	Ultimate tensile strength	Yield strength	Elong.
	wt. %		^{0} C (^{0} F)		g/cm^3	MPa (KSI)	MPa (KSI)	%
316L	None	As- sint	1316 (2400)	D. A.	7.11	510 (74)	310 (45)	12
434L	None	As- sint	1316 (2400)	D.A.	7.09	428 (62)	247 (36)	17
409LNi	None	As- sint	1330 (2425)	100% H2	7.3	600 (87)	490 (71)	9
410L + C (410)	0.15	Sintered + tempered	1230 (2250)	100% H2	6.9	690 (100)	560 (82)	1.2
410L + C (410)	0.15	Heat treated	1230 (2250)	100% H2	6.9	830 (120)	720 (105)	1.5
410L + C (420)	0.3	Sintered + tempered	1230 (2250)	100% H2	6.9	900 (130)	830 (120)	0.8
410 + C (420)	0.3	Heat treated	1230 (2250)	100% H2	6.9	980 (142)	900 (130)	0.8

In the present study efforts were made to determine the mechanical properties achievable with the press and sinter PM process, when the thermal history and carbon contents are kept within well defined ranges. Properties were determined in the as-sintered, as-solution annealed, and after aging at two different temperatures. Test specimens were sintered in a single run in a batch furnace, followed by rapid cooling. Solution annealing and aging treatments were carried out at a well established commercial heat treating facility, adhering to SAE Aerospace Material Specification for 17-4 PH alloy (AMS 2759/3D).

Carbon contents of the test specimens were varied within the overall carbon specification of 0.07% max., in order to determine the effect of small variations in the carbon content on mechanical properties. The primary goal was to identify the thermal cycle (with or without heat treatment) and the specific range of carbon content that can lead to highest possible tensile strength, without a severe reduction in ductility. It was considered that a 4% tensile elongation would be the acceptable ductility level for 17-4 PH made by the single-press-single-sinter route.

MATERIALS

In this study a commercially available 17-4 PH grade of powder, manufactured by North American Hoganas, was used. This was a water atomized powder having a nominal particle size of –100 mesh, with a -325 mesh content of 47 wt. %. Table 1 lists the chemical composition of the powder along with MPIF chemistry specification for MIM grade 17-4 PH alloy. The powder was lubricated with 1.0% lithium stearate. The apparent density of the lubricated powder was 2.78 g/cm^3. Four test blends of the powder were employed in the study, each with a different amount of graphite addition. The graphite addition amounts were 0.0%, 0.06%, 0.09% and 0.12% – representing Sample Groups A, B, C, and D, respectively.

Table 2: Powder chemical composition (wt %)

Element	Cr	Ni	Cu	Si	Mn	Cb +Ta	C	S	P	Fe
MIM Spec	15.5 to 17.5	3.0 to 5.0	3.0 to 5.0	1.0 max	1.0 Max	0.15 to 0.45	0.07 max	0.03 max	0.04 max	Bal.
Powder used	17.2	3.8	3.7	0.9	0.24	0.35	0.02	0.004	0.014	Bal.

EXPERIMENTAL PROCEDURE

Samples in the form of dog bone tensile bars (per MPIF Test Method 10) were compacted from the four powder blends (Sample Groups A, B, C, and D). For all samples, the green density was kept at 6.30 g/cm^3 , which was achieved by compacting under a pressure of 760 MPa (55 TSI). Delubrication and sintering were carried out in a batch furnace under an atmosphere of 100% hydrogen. The sintering temperature was 1275^{0}C (2327^{0}F), and the time at temperature was 45 minutes. After sintering, samples were cooled rapidly from the sintering temperature at a cooling rate of 2^{0}C / sec.

Density measurements were carried out on the as-sintered specimens. Three samples from each group were set aside for tensile testing in the as-sintered condition. All other sintered samples, from all four sample groups, were given a solution annealing treatment in a single furnace run. Solution annealing was carried out at 1065^{0}C (1950^{0}F) in a low pressure hydrogen atmosphere for 90 minutes, per SAE Aerospace Material Specification AMS 2759/3D. The cooling rate from the solution anneal temperature was 2^{0}C / sec.

Three samples from each of the four sample groups were tensile tested in the solution annealed condition. Three samples from each sample group were given an aging treatment at 482^{0}C (900^{0}F) for a duration of two hours in a nitrogen atmosphere (H900 condition). Three other samples from each sample group was given an aging treatment at 552 ^{0}C (1025 ^{0}F) for four hours in a nitrogen atmosphere (H1025 condition). All solution annealing and aging treatments were carried out at Solar Atmospheres Heat Treat facility in Hermitage, PA. Tensile testing of all samples was carried out at Chicago Spectro Services Laboratory, Chicago, IL, in accordance with ASTM Test Method E-8. All samples except one (C-8) broke in the gage section. Elongation (plastic) was determined by the physical measurement of broken specimens.

The broken tensile specimens were used for carbon, oxygen and nitrogen analyses. Carbon analyses were carried out in a LECO Model CS 244 carbon and sulfur analyzer. Oxygen and nitrogen analyses were carried out in a LECO Model TC 436 analyzer.

Metallographic specimens were prepared from the grip sections of the broken tensile specimens. Glyceregia was used as etchant for microstructure development.

RESULTS

Table 3 lists the residual carbon contents of as-sintered samples from all four sample groups. The sintered densities ranged from 7.15 to 7.22 g/cm^3, with the higher carbon containing samples exhibiting lower densities. This is considered to be due to the relatively larger amounts of acicular martensite forming in the higher carbon containing samples. A further decrease in carbon content occurred during solution annealing, for all four sample groups. As expected, the oxygen contents of the sintered samples decreased with increasing graphite addition. Group A, which was sintered without any graphite addition also underwent a reduction in oxygen content, from 2025 ppm in the original powder to 1678 ppm after sintering. The nitrogen contents of all sintered samples were quite low, falling in the range of 40 to 70 ppm.

Table 3: Residual carbon contents and sintered densities of as-sintered materials

Sample Group	**Graphite addition, wt %**	**Carbon content , wt %**	**Sintered density, g/cm^3**
A	None	0.023	7.22
B	0.06	0.040	7.2
C	0.09	0.059	7.17
D	0.12	0.074	7.15

Tables 4, 5, 6 and 7, show the mechanical properties of the samples in the as-sintered, solution annealed, solution annealed and aged at 482^{0}C (900^{0}F), and solution annealed and aged at 552^{0}C (1025^{0}F) conditions, respectively.

Table 4: Mechanical properties and carbon contents of samples tested in the as-sintered condition

			Condition: As-Sintered				
Sample Group	Sample ID	Ultimate tensile strength	Yield strength	Elong.	Carbon	Oxygen	Hardness
		MPa (KSI)	MPa (KSI)	%	%	ppm	HRB
A	A-1	860 (124.7)	762 (110.5)	3.6	0.025	1568	80
	A-2	879 (127.5)	774 (112.2)	1.9	0.024	1666	89
	A-3	869 (126.0)	(NA)	2.0	0.020	1800	87
	Average	**869 (126.1)**	**768 (111.4)**	**2.5**	**0.023**	**1678**	**89**
B	B-1	849 (123.1)	774 (112.0)	3.2	0.040	1192	96
	B-2	856 (124.1)	779 (113.0)	2.9	0.040	1118	83
	B-3	863 (125.2)	(NA)	2.6	0.040	1100	88
	Average	**856 (124.1)**	**775 (112.5)**	**2.9**	**0.040**	**1134**	**89**
C	C-1	869 (126.0)	785 (113.9)	3.0	0.062	1176	87
	C-2	876 (127.1)	785 (113.8)	3.2	0.060	1020	83
	C-3	876 (127.0)	(NA)	3.0	0.055	1155	85
	Average	**874 (126.7)**	**785 (113.8)**	**3.1**	**0.059**	**1117**	**85**
D	D-1	867 (125.7)	783 (113.6)	2.5	0.075	1082	84
	D-2	851 (123.4)	769 (111.3)	2.2	0.079	1064	84
	D-3	847 (122.8)	(NA)	2.8	0.069	952	80
	Average	**856 (124.0)**	**775 (112.4)**	**2.5**	**0.074**	**1033**	**83**

Table 5: Mechanical properties and carbon contents of samples tested in the solution annealed condition

			Condition: Solution Annealed				
Sample Group	Sample ID	Ultimate tensile strength	Yield strength	Elong.	Carbon	Oxygen	Hardness
		MPa (KSI)	MPa (KSI)	%	%	ppm	HRB
A	A-4	865 (125.5)	751 (109.0)	4.4	0.022	1560	89
	A-5	747 (108.4)	665 (96.4)	4.7	0.021	1484	90
	A-6	835 (121.1)	736 (106.8)	4.4	0.019	1610	90
	Average	**816 (118.3)**	**718 (104.1)**	**4.5**	**0.021**	**1551**	90
B	B-4	841 (122.0)	758 (109.9)	3.4	0.032	1183	86
	B-5	932 (135.3)	757 (109.5)	4.1	0.037	1105	84
	B-6	857 (124.3)	774 (112.2)	3.7	0.035	1365	88
	Average	**877 (127.2)**	**762 (110.5)**	**3.7**	**0.035**	**1218**	**86**
C	C-4	819 (118.8)	736 (106.7)	3.1	0.052	1172	85
	C-5	845 (122.5)	757 (109.4)	3.5	0.059	1250	87
	C-6	823 (119.3)	735 (106.3)	2.8	0.057	1012	81
	Average	**829 (120.2)**	**740 (107.5)**	**3.1**	**0.056**	**1145**	**85**
D	D-4	872 (126.5)	788 (114.3)	1.3	0.067	1070	84
	D-5	830 (120.4)	747 (108.3)	2.8	0.056	1092	85
	D-6	830 (120.4)	725 (105.2)	2.0	0.067	920	82
	Average	**844 (122.4)**	**754 (109.3)**	**2.0**	**0.063**	**1027**	**84**

Table 6: Mechanical properties and carbon contents of solution annealed and aged samples - Aged at 482^0C (900^0F) – H900 condition

			Condition: Solution annealed and aged (482^0C,900^0F)				
Sample Group	Sample ID	Ultimate tensile strength	Yield strength	Elong.	Carbon	Oxygen	Hardness
		MPa (KSI)	MPa (KSI)	%	%	ppm	HRB
A	A-7	1135 (164.6)	1048 (152.0)	1.1	0.021	1732	99
	A-8	1138 (165.0)	1047 (151.9)	1.6	0.022	1640	96
	A-9	1137 (164.9)	1048 (152.0)	1.4	0.024	1673	99
	Average	**1136 (164.8)**	**1048 (152.0)**	**1.4**	**0.022**	**1682**	**98**
B	B-7	1082 (157.0)	992 (143.9)	1.4	0.038	1181	94
	B-8	1087 (157.6)	999 (144.9)	1.1	0.033	1146	95
	B-9	1068 (154.9)	948 (137.5)	1.4	0.035	1236	94
	Average	**1079 (156.5)**	**980 (142.1)**	**1.3**	**0.035**	**1187**	**94**
C	C-7	1000 (145.0)	916 (132.9)	1.8	0.060	1118	95
	C-8	1004 (145.7)	920 (133.4)	NA	0.059	1197	96
	C-9	989 (143.4)	901 (130.7)	1.2	0.059	1258	92
	Average	**998 (144.7)**	**912 (132.3)**	**1.5**	**0.059**	**1158**	**94**
D	D-7	966 (141.4)	871 (126.4)	0.6	0.068	956	97
	D-8	969 (140.5)	885 (128.4)	1.3	0.068	1030	98
	D-9	983 (142.6)	893 (129.5)	0.9	0.066	1036	96
	Average	**973 (141.4)**	**885 (128.3)**	**0.9**	**0.067**	**1007**	**97**

Table 7: Mechanical properties and carbon contents of solution annealed and aged samples - Aged at 552^{0}C (1025^{0}F) – H1025 condition

			Condition: Solution annealed and aged (552^{0}C,1025^{0}F)				
Sample Group	Sample ID	Ultimate tensile strength	Yield strength	Elong.	Carbon	Oxygen	Hardness
		MPa (KSI)	MPa (KSI)	%	%	ppm	HRB
A	A10	1034 (150.0)	951 (137.9)	3.2	0.021	1712	95
	A-11	1032 (149.7)	940 (136.4)	3.1	0.020	1536	94
	A-12	1029 (149.3)	946 (137.2)	3.3	0.021	1440	95
	Average	**1032 (149.7)**	**946 (137.2)**	**3.2**	**0.021**	**1579**	**95**
B	B-10	940 (136.4)	855 (124.3)	3.7	0.035	1134	93
	B-11	960 (139.2)	857 (127.2)	3.7	0.032	1146	93
	B-12	946 (137.2)	827 (119.9)	4.6	0.037	1133	92
	Average	**949 (137.6)**	**854 (123.8)**	**4.0**	**0.035**	**1138**	**93**
C	C-10	891 (129.3)	808 (117.2)	1.7	0.054	1183	92
	C-11	940 (136.4)	837 (121.4)	1.6	0.056	1142	92
	C-12	968 (140.4)	884 (128.2)	2.0	0.055	1158	92
	Average	**934 (135.4)**	**843 (122.3)**	**1.8**	**0.055**	**1161**	**92**
D	D-10	867 (125.7)	783 (113.6)	1.9	0.062	965	80
	D-11	892 (129.4)	802 (116.3)	1.7	0.060	1135	87
	D-12	925 (134.1)	840 (121.9)	1.1	0.063	1082	91
	Average	**894 (129.7)**	**809 (117.3)**	**1.6**	**0.062**	**1060**	**86**

Micro-indentation hardness measurements were made only on the heat treated samples, taken from Sample Groups A and B. The results are shown in Table 8. These results parallel the tensile strength data.

Table 8: Micro-indentation hardness of selected sample sets

	Micro-indentation Hardness, HV_{100}	
Metallurgical condition	Group A	Group B
As- Solution annealed	349	363
Aged at 482 ^{0} C (900 ^{0}F)	448	533
Aged at 552 ^{0}C (1025 ^{0}F)	401	434

MICROSTRUCTURE

Overall, the microstructures were fairly clean, given the fact that PM materials made from water atomized powders inevitably contain some fine oxides. The pores were well rounded, which is desirable from the ductility point of view. Within each set of heat treated samples, there was a good degree of uniformity in their martensite distribution. All samples contained approximately 15% delta ferrite.

Figure 1 shows the microstructure of a 0.035% carbon containing material in the solution annealed condition. Lath type martensite is seen throughout, without the presence of any precipitates.

Figure 2 is the microstructure of a 0.035% carbon containing sample in the H900 age hardened condition (482^0C, 900^0F). Here also the matrix consists of predominantly lath type martensite, with no visible precipitates.

Figure 3 is a microstructure of a 0.059% carbon containing sample in the H900 age hardened condition (482^0C, 900^0F). The high carbon content has led to formation of acicular type martensite. There is no indication of any visible precipitates in the microstructure.

Figure 4 shows the microstructure of a 0.035% carbon containing sample in the H1025 age hardened condition (552^0C, 1025^0F). Here, some of the precipitates are large enough to be visible under the optical microscope. The matrix is predominantly comprised of lath type martensite.

Figure 5 shows the microstructure of a 0.060% carbon containing sample heat treated by H1025 age hardening at 552^0C (1025^0F). Here traces of precipitates are seen along some of the grain boundaries.

Figure 6 shows the microstructure of a 0.040% carbon containing sample in the as-sintered condition. Precipitates formed here are large enough to be visible under the optical microscope.

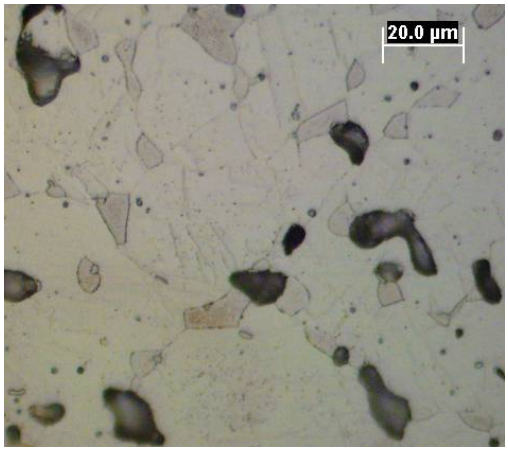


Figure 1: Photomicrograph of a 0.035% carbon containing sample in the solution annealed condition.

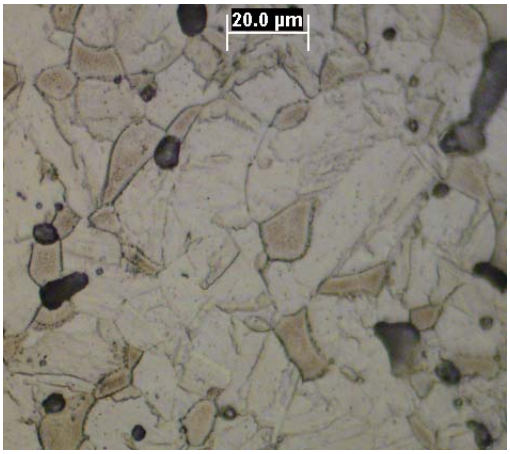


Figure 2: Photomicrograph of a 0.035% carbon containing sample in the age hardened condition (482^0C, 900^0F) – H900

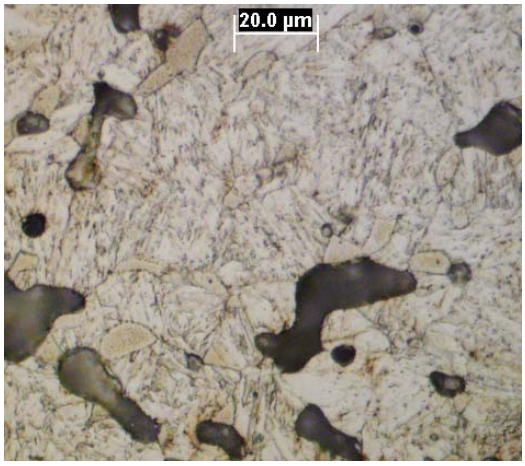


Figure 3: Photomicrograph of a 0.059 % carbon containing sample in the age hardened Condition (482^{0}C, 900 ^{0}F) – H900 condition

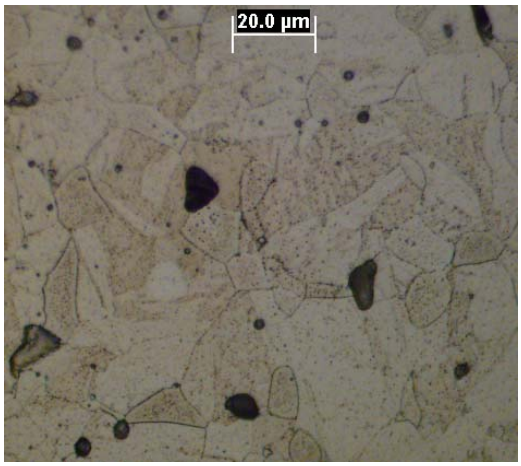
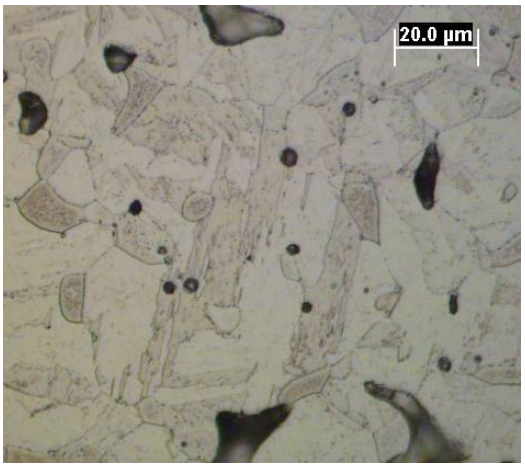


Figure 4: Photomicrograph of a 0.035% carbon containing sample, age hardened at 552 ^{0}C, (1025 ^{0}F) – H1025 condition

Figure 5: Photomicrograph of a 0.055% carbon containing sample age hardened at 552^{0}C (1025^{0}F) – H1025 condition.



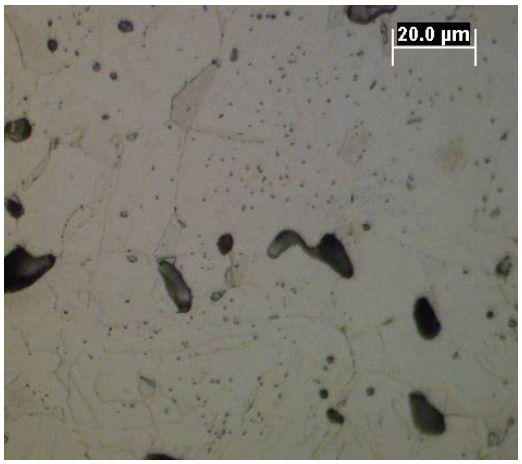


Figure 6: Photomicrograph of a 0.040% carbon containing sample in the as-sintered condition.

DISCUSSION

The strength levels achieved under all four thermal histories are quite impressive. The ultimate tensile strength of the as-sintered materials are similar to what is typically achievable with martensitic 420 SS (410L + 0.3%C + heat treatment, Table 1), but with higher ductility. However, it must be noted here that significantly wider variations in strength and ductility have been observed with as-sintered 17-4 PH processed in commercial furnaces. This is presumed to be caused by wider variations in the cooling rate and the residual carbon contents in those materials. The findings here are, hence, an indication that with rapid cooling and efficient delubrication (which primarily influences residual carbon content) it is feasible to achieve consistently high mechanical strength and acceptable ductility in the alloy in the as-sintered condition. The cooling rate employed in this study was 2^0C /sec (4^0F/sec), which is somewhat faster than the cooling rates typically used for sinter hardening of PM steels. A slightly slower cooling rate may still be acceptable here, as long as it is maintained well. The results of the as-sintered samples also show that the residual carbon content, in the range of 0.02 to 0.07%, has no influence on the mechanical properties of the alloy. Nevertheless, the strength levels of these as-sintered materials are remarkably lower than those of the fully heat treated (age hardened) materials.

The solution annealed samples exhibit lower strength levels in comparison to the as-sintered and the two sets of age hardened samples. Here again, there is no apparent dependency of strength on the residual carbon content within the range of carbon content studied. There is however, a strong dependency of ductility on the residual carbon content.

The results of the two sets of age hardened samples show a significant dependence of strength on the residual carbon content. The two lower carbon containing materials exhibit the highest strength levels. In these two sample sets, carbon contents in the range of 0.02 to 0.04% are found to produce optimum combinations of strength and ductility. This finding is similar to what is recognized by researchers in the MIM industry. In the MIM processing of 17-4 PH, it is recognized that a carbon content in the range of 0.02 to 0.04% leads to optimum combination of strength and ductility, although the broad specification range for carbon is 0.00 to 0.070% [5]. In this study, the nitrogen contents of all samples were low, below 70 ppm. Since nitrogen has similar effect on martensite formation as carbon, control of the nitrogen content is equally important for maximizing ductility.

The lower age hardening temperature of 482^0C (900^0F) yielded very high strength levels, but at the expense of ductility. The ductility levels of less than 1.5% seen here are undesirable for most structural applications (Figure 6). If by some modification of the compaction and sintering process, the sintered density can be increased further, then perhaps a useful combination of high strength and acceptable ductility can be achieved by the use of this low age hardening temperature.

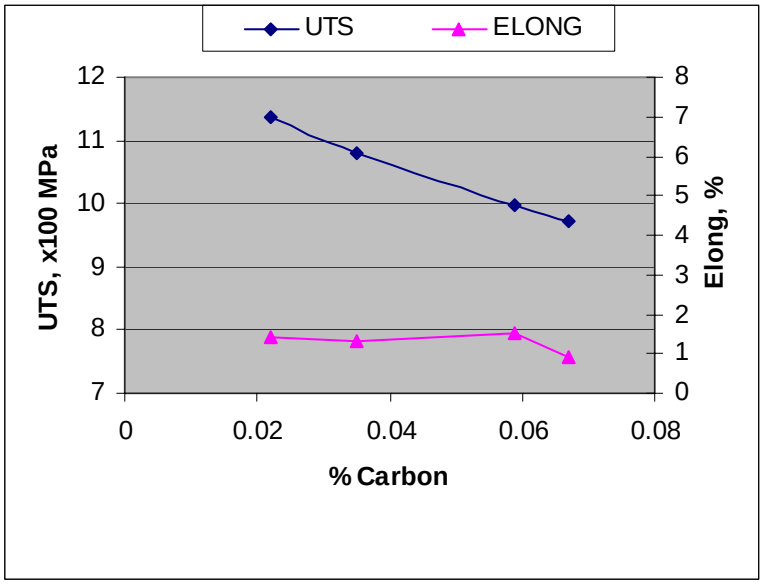


Figure 7: Effect of residual carbon content on UTS and elongation for 482^{0}C (900^{0}F) age hardened materials – H900 condition.

With the level of sintered density employed in this study (7.15 to 7.22 g/cm^3), the 552 ^{0}C (1025^{0}F) age hardening treatment does lead to satisfactory ductility, provided that the residual carbon content is held below 0.04% (Figure 7). The mechanical strength and ductility achieved here are superior to those achieved with PM martensitic, heat treated 420 SS.

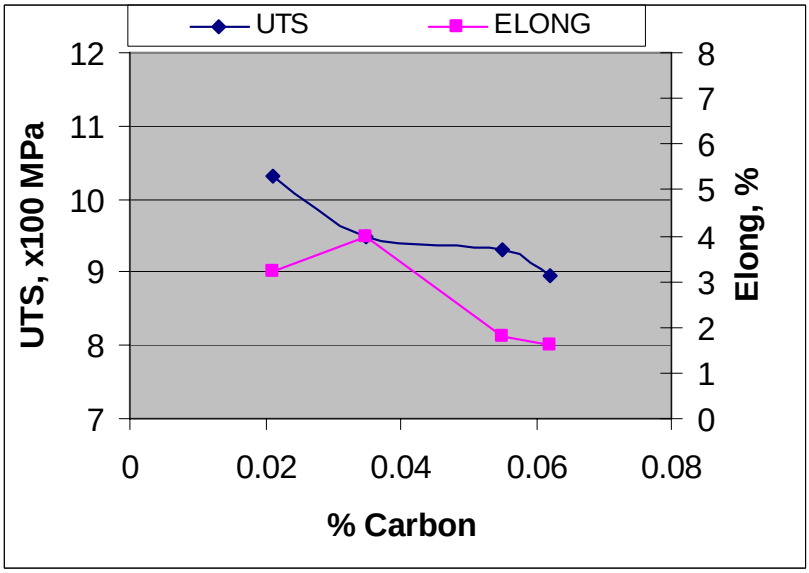


Figure 8: Effect of residual carbon content on UTS and elongation for 552^{0}C (1025^{0}F) age hardened materials, H1025 condition.

CONCLUSIONS

Despite the relatively low sintered densities achieved with press and sinter processing, useful combinations of high strength and moderate ductility can be achieved with 17-4PH alloy when solution annealed and age hardened at 552 ^{0}C (1025 ^{0}F).

It is highly essential that the residual carbon content be held at or below 0.04%, in order to maximize both strength and ductility in the age hardened alloy.

In order to achieve consistently high mechanical strength and acceptable ductility in the as-sintered 17-4 PH, the residual carbon content need be held below 0.07%, and the cooling rate from the sintering temperature must be fairly rapid.

Carefully processed press and sinter 17-4 PH can provide strength and ductility combinations that are currently unachievable with ferritic, austenitic, and martensitic PM stainless steels.

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