Effects of Tin Powder on Properties of Sintered Stainless Steels

**Nattaya TOSANGTHUM[1], Piyanuch MUANGTONG[2], Ornmanee COOVATTANACHAI[1],
Monnapas MORAKOTJINDA[1], Thanyaporn YODKAEW[1], Pongsak WILA[1],
Rungthip KRATAITONG[1], Bhanu VETAYANUGUL[1] and Ruangdaj TONGSRI[1]**

*[1]National Metal and Materials Technology Center (MTEC), 114 Thailand Science Park,
Paholyothin Road, Klong 1, Klong Luang, Pathumthani, 12120 Thailand
[2]Department of Production Technology, Faculty of Engineering, King Mongkut's
Institute of Technology North Bangkok, 1518 Pibulsongkram RD.,
Bangsue, Bangkok, 10800 Thailand.*

Abstract

It was found that addition of 4 wt.% of gas-atomized tin (Sn) powder to stainless steel powders could alter sintered properties of P/M stainless steels. For stainless steel series 300 powders, Sn powder addition resulted in improved tensile properties and hardness. It was speculated that the liquid Sn, formed during sintering process, acted as either a sintering activator or a solvent for nickel (Ni) dissolution. Sintering activation existed because the liquid Sn acted as a diffusion path for powder particle constituent atoms. Dissolution of Ni in Sn was simply due to diffusion of Ni atoms from stainless steel series 300 particles in the liquid Sn. Addition of Sn powder to stainless steel series 400 powders caused extremely adverse effects on tensile properties. Only hardness of the sintered stainless steel series 400-Sn materials could be examined.

Introduction

Powder metallurgy (P/M) involves forming of metal powders into useful metallic parts. In a conventional P/M process, metal powders are compacted, using high pressure, into green parts the strength of which is just sufficient for handling only. The green parts are then heated up to a certain temperature below a melting point of a principal powdered metal, under suitable reducing atmosphere. During heating, sintering phenomenon (weldment of contact interfaces between powder particles) causes densification and strengthening of the parts. The basic P/M process has been employed for producing engineering metallic parts, which are used in many applications including aerospace, agriculture, appliances, automotive, building and construction, chemical, electrical and electronic, hardware, industrial, jewelry, marine, medical office equipment, recreation and leisure.[1]

Sintered 316L stainless steel has been considered as a replacement for sintered ferrous alloys due to its superior mechanical properties and corrosion resistance. Demand for higher performance sintered 316L stainless steels exists. Attempt has been carried out to improve the performance of sintered 316L stainless steel. Addition of nickel and copper powders to austenitic 316L stainless steel powder resulted in modified densification behaviors.[1] The composition of the admixed powder, which exhibited optimum mechanical properties was 316L+6wt.%Ni. Addition of Cu powder to the admixed 316L+Ni powders resulted in a decrease of sintered density, mechanical properties and shrinkage after sintering. Although Ni powder is a promising alloying material for improvement of the sintered 316L stainless steel property, it is not economically feasible due to its high cost.

High strength sintered 316L stainless steel could be obtained by modification sintering process. Increasing sintering time for the 316L alloy resulted in slightly improved strength.[2] However, prolonged sintering time caused detrimental effects, such as grain growth and particle coarsening, to the sintered materials.[3] Modification of sintering atmosphere compositions

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by varying nitrogen content resulted in improvement of ultimate tensile strength (UTS) and yield strength of sintered materials.[4] Increase of strength with nitrogen content is attributed to solid solubility of nitrogen at the interstitial sites in the powder particle matrix.[5]

Liquid phase sintering of 316L admixed with a liquid forming powders showed evidence of material property change.[6] The transient liquid phase reaction between iron-nickel and aluminium to form an intermetallic (Fe, Ni)$_3$Al modified densification of 316L stainless steel powder and resulted in a change of its macrohardness and corrosion resistance.

During solid state sintering, various phenomena occur for example surface diffusion, vapour transport and plastic flow.[7] Among these phenomena, surface diffusion is the most important. Atomic diffusion of alloy powder constituents from bulk to the points of contact between powder particles (the areas where powder particles weld with one another) controls the sintering process. The presence of a liquid phase, formed before the commencement of solid-state sintering of the base powder particles, may ease diffusion of the alloy powder constituents. With this assumption, effects of a liquid-phase sintering using Sn powder on properties of sintered stainless steels have been studied.

Experimental Procedures

The powders employed for this investigation included stainless steel (series 300 and 400) and nitrogen-atomized Sn powders. Average particle size of the Sn powder was less than 32 μm. A fixed amount of the Sn powder (4 wt. %) was admixed with stainless steel powders before being compacted into tensile test bars (TTBs) with a green density of 6.50 ± 0.05 g/cm^3 All the green TTBs were delubricated at 600°C in argon. Sintering of the stainless steel series 300 powder compacts was performed at 1300°C for 35 minutes in pure hydrogen atmosphere. Sintering of the series 400 powder compacts was performed at 1350°C for the same holding time.

The sintered materials were tested and characterized as follows. Sintered density was measured by using the MPIF standard 42. Mechanical (tensile) properties of the sintered tensile test bars were measured by using a universal testing machine. Hardness of the sintered specimens was carried out using a hardness tester (Rockwell scale B). Microstructural observation was done by using optical microscopy. Chemical analysis was performed by using EDS line scanning.

Results and Discussion

Sintered Properties

Regardless of steel types, sintered densities of the sintered 4 wt. % Sn-added stainless steels were slightly lower than those of the sintered straight stainless steels (Table 1). For the case of sintered series 300 materials, lower sintered density may be attributed to pore size expansion due to the liquid tin accelerate atomic diffusion whereas that of the series 400 materials is due to additional pores caused by Sn particle disappearance (see # (3.2) microstructure). The results contradicted slightly with the previous study on the sintered 316L-Sn material.[8, 9] It was reported that the sintered density of the sintered 316L-Sn materials reached optimum value when 4 wt. % of Sn powder was added. However, the cause of difference between the results obtained in this study and those reported in the previous studies may be the increased sintering holding time of 45 minutes.

Table 1. Properties of the sintered Sn-added stainless steels

| Materials	Sintered density (g/cm3)	Hardness (HRB)	Elongation (%)	Tensile (MPa)	Yield (MPa)
304L	7.17	42.57	20.27	403.72	222.32
304L-4wt.%Sn	7.01	44.20	20.73	435.10	252.26
316L	7.17	40.62	17.25	388.66	221.62
316L-4wt.%Sn	7.03	48.60	20.80	452.25	264.80
303L	7.13	44.44	11.06	377.45	236.16
303L-4wt.%Sn	7.11	61.74	7.53	383.75	263.54
310L	6.98	53.60	3.50	310.46	249.71
310L-4wt.%Sn	6.87	55.28	12.76	396.66	250.22
409L	7.30	58.28	16.96	445.65	279.95
409L-4wt.%Sn	7.25	84.08	*	*	*
410L	7.35	49.55	20.93	421.07	254.83
410L-4wt.%Sn	7.22	74.22	*	*	*
430L	7.06	58.84	14.33	422.03	286.93
430L-4wt.%Sn	7.11	70.50	*	*	*
434L	7.28	61.40	17.14	466.61	321.97
434L-4wt.%Sn	7.21	80.70	*	*	*

* The sintered materials became brittle so they could not be tested.

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Under experimental P/M processing conditions employed in this study, addition of 4 wt. % Sn powder to stainless steels series 300 powders resulted in significantly improved mechanical properties (Table 1). In contrast, addition of Sn powder to stainless steel series 400 powders caused extremely adverse effects on tensile properties. Only hardness of the sintered series 400-Sn materials could be examined.

Microstructure

For the stainless steel series 300 powders, admixing with tin powder resulted in grain growth and pore size expansion (Figure. 1(a) and (b)). Grain growth was frequently observed in the materials sintered for prolonged times.[4] Surprisingly, grain coarsening in the sintered tin-added stainless steels series 300 even occurred in normal sintering conditions. This may indicate that liquid tin accelerates atomic diffusion-related processes occurring during heating of the powder compacts. Previous studies[8-10] reported that the grain size was increased with increasing liquid tin content of up to 6 wt. %. This phenomenon contradicted with the behaviors of the sintered materials, such as W-Ni, VC-Co, W-Ni-Fe and Pb-Sn.[11] Grain size of the sintered W-Ni, VC-Co, W-Ni-Fe and Pb-Sn materials increased with increasing liquid volume fraction.
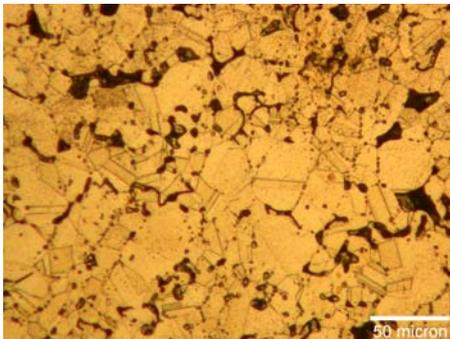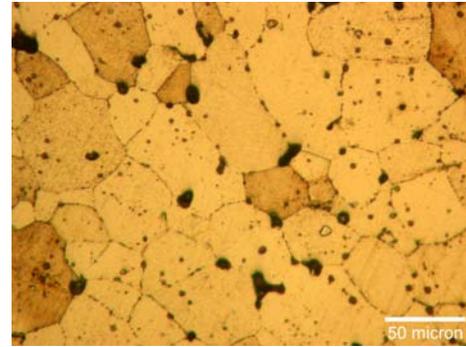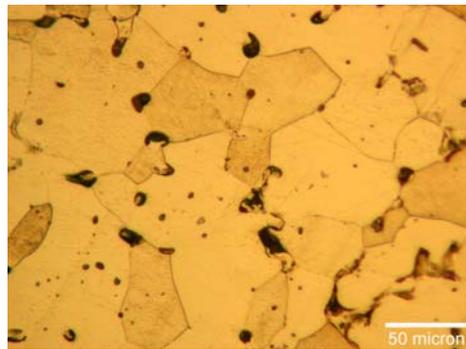
(a) Sintered 316L
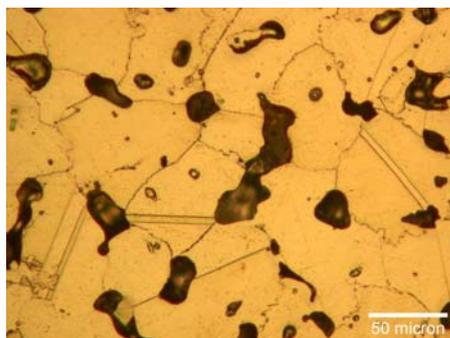
(b) Sintered 316L-4 wt. % Sn

The sintered series 400-Sn materials showed similar microstructures to those of the sintered straight series 400 materials (Figure. 1(c) and (d)). Some pores, created by Sn particle disappearance, were observed in addition to those initiated by original voids in the green compacts.
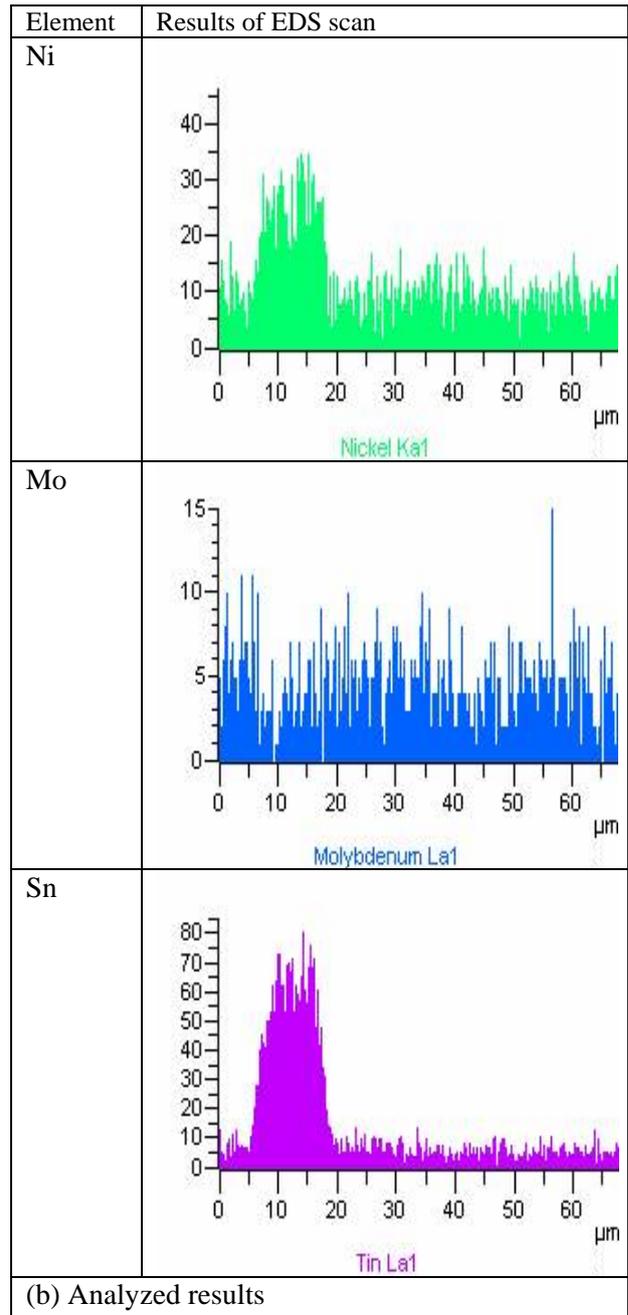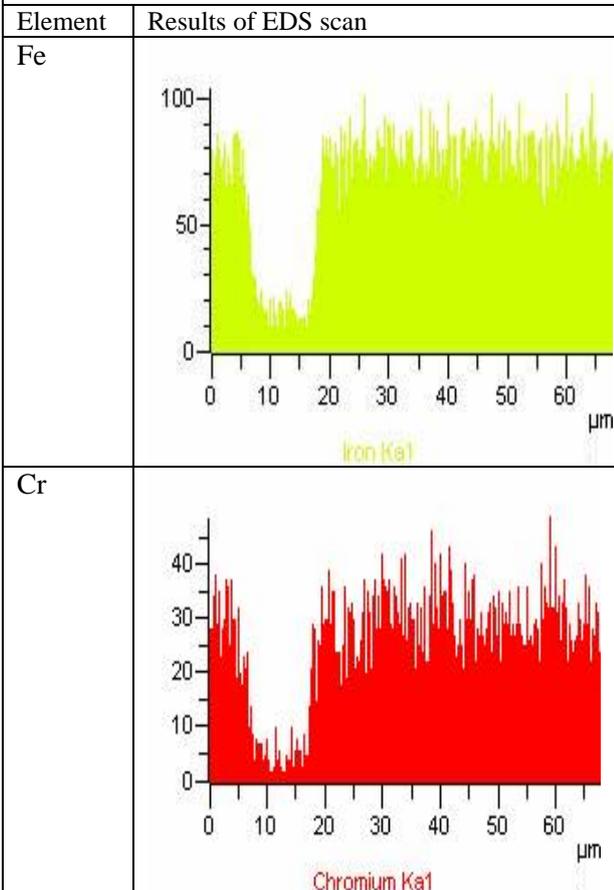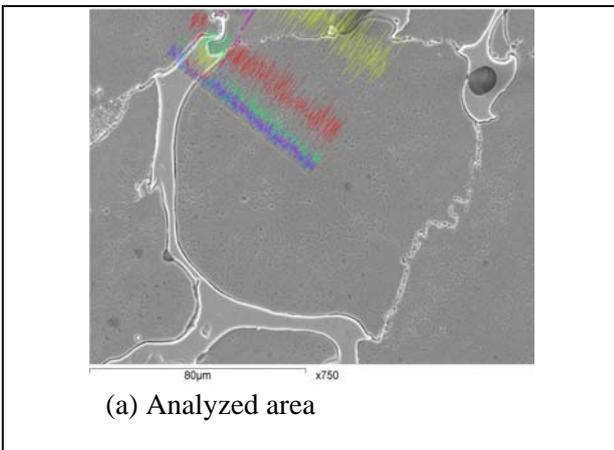
(c) Sintered 409L

(d) Sintered 409L-4 wt. % Sn

Figure 1. Microstructures of sintered stainless steels.

Chemical Analysis by EDS

The sintered 316L-Sn material was selected as an example of P/M stainless steels for chemical analysis. EDS line scanning was performed across 316L-Sn-316L grains (Figure. 2) During scanning process, the intensity of characteristic energy of the specified element was counted and plotted against the scan distance. It was found that there were fewer amounts of Fe, Cr, and Mo elements in the tin phase compared to those in the 316L grains. In contrast, an abundance of Ni and Sn elements was observed in the tin phase.

It is speculated here that the liquid Sn, formed during sintering process, acted as either a sintering activator or a solvent for Ni dissolution. Sintering activation exists because the liquid Sn

acts as a diffusion path for constituent atoms of the 316L particles. During heating the powder compact, elemental atoms diffuse from 316L particles to their surfaces. Some of the particle surfaces are contacting areas between 316L particles. These contacting areas are where sintered necks are formed and grown. For the particle surfaces contacting directly with the liquid Sn, the diffused atoms dissolve and diffuse through the liquid Sn. Transportation of elemental atoms is supposed to be enhanced in the liquid phase compared to that in empty pores. In other words, the liquid Sn is acts like a path for elemental atom diffusion, which is a principal factor for sintering process.[7]

(a) Analyzed area

Element	Results of EDS scan
Fe	
Cr	

Element	Results of EDS scan
Ni	
Mo	
Sn	
(b) Analyzed results	

Figure 2. EDS line scanning of the 316L-Sn-316L area in the sintered 316L-Sn material.

The presence of Ni-rich Sn phase in the sintered 316L-Sn material is due to dissolution of Ni in Sn. During heating a powder compact, the constituent atoms are dissolved in the liquid Sn. During cooling, some excessive atoms are ejected from the liquid Sn and diffuse back into the 316L grains. The remaining high Ni content in the solid Sn phase indicates either high solid solubility of Ni in Sn or the formation of Ni-Sn compounds. Details of Ni-rich phase formation and its strengthening effect on the sintered Sn-added series 300 stainless steels will be further investigated.

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Conclusions

For stainless steel series 300 powders, Sn powder addition resulted in improved tensile properties and hardness. It was speculated that the liquid Sn, formed during sintering process, acted as either a sintering activator or a solvent for nickel (Ni) dissolution. Sintering activation existed because the liquid Sn acted as a diffusion path for powder particle constituent atoms. The presence of Ni in Sn was simply due to diffusion of Ni atoms from stainless steel series 300 particles to dissolve in the liquid Sn. Addition of Sn powder to stainless steel series 400 powders caused extremely adverse effects on tensile properties. Only hardness of the sintered stainless steel series 400-Sn materials could be examined.

Acknowledgment

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