The study on the characterization of sintered hot forging and austenite stainless steels

Sittipong Eiumtadanai¹, Sithipong Mahathanabodee¹, Ruangdaj Tongsri², Bhanu Vetyanugul², Sumate, Poomiapiradee³,*

¹Department of Production Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok (KMUTNB), 1518 Pracharat 1, Bang-Sue, Wongsawang, Bangkok, 10800, Thailand
²Particulate Materials Processing Technology Laboratory (PMPT), National Metal and Materials Technology Center, 114 Paholyothin Road, Khlong Nueng, Khlong Luang, Pathum Thani, 12120, Thailand
³Thailand Institute of Scientific and Technological Research, 35 Mu 3 Technopolis, Tambon Khlong Ha, Amphoe Khlong Luang, Pathu thani 12120, Thailand

* Corresponding Author: 20sittipongeiu@gmail.com

Abstract

The powder metallurgical (PM) process, consisting of compaction and sintering, is commonly used to produce sintered structural parts applied in various industrial fields. Sintered parts always have porosity due to limited materials transport by solid-state diffusion from powder particles to voids between them. Sintered specimens with low porosity show superior mechanical properties. Hot forging is one of processes for enhancing density of sintered parts. This process was applied to sintered austenitic stainless steels (303L, 304L, 310L and 316L). The hot-forged specimens showed increased density. This led to remarkable increase of hardness (up to 5 times). Due to the hot working nature of the process, microscopic changes in the hot-forged specimens during the process were examined. It was found that grain size and volume fraction of twins were significantly decreased.

Keywords: Powder metallurgy, Stainless steel, Hot forging, Mechanical properties

1. Introduction

Powder metallurgy (PM) involves metal and alloy parts manufacturing from metal and alloy powders [1, 2]. The use of PM for producing sintered stainless-steel parts minimizes the need for machining and deformation operations and thus allows economical production of near net-shaped products [3]. Sintered stainless steels possess promising properties such as corrosion and oxidation resistance, appreciable mechanical strength as well as good formability [4]. Due to such promising properties, they have been applied in several fields including automotive [5], biomedical [6, 7] and others [8].

Typical sintered stainless steels contain pores, which show adverse effects on mechanical [7] and chemical [9] properties. Thus, some research works [10-12] have been conducted with attempt to get rid of porosity in sintered metals and alloys by taking the benefit of liquid phase sintering [13]. The increase
of sintered density due to porosity reduction by liquid phase sintering is traded off by elongation reduction due to the presence of intergranular phases.

Hot forging is one of hot forming processes used to form shaped parts. It applies loads on a heated specimen to cause metal deformation, transformation and shape formation. In addition, hot forging is also used to refine the microstructure and to redistribute the alloying element producing high quality steel [14]. The microstructural refinement in hot-deformed stainless steels (bulk alloys) is due to dynamic recrystallization (DRX) [15, 16].

In this work, it is expected that hot forging would enhance density of sintered austenitic stainless steels (303L, 304L, 310L and 316L) due to due to metal flow or deformation during hot working. Since the presence of porosity in sintered austenitic stainless steels may affect the driving force for some dynamic softening processes it is thus worth investigating microstructural change after hot forging as shown in Figure 1.

![Flowchart showing experimental works](image)

**Figure 1.** Flowchart showing experimental works

### 2. Materials and Methods

#### 2.1 Specimen preparation

The flowchart showing experimental works is given in Figure 1. Four austenitic stainless steel powders (303L, 304L, 310L and 316L) with composition given in Table 1 were used for this investigation. Each powder was mixed with 1 wt% lubricant and cold compacted into a cylinder-shape specimen with dimensions of 14.80 mm diameter and 10.0 mm height under a constant pressure of 58.5 bars. After compaction, green specimens were sintered at 1280°C for 45 minutes under pure hydrogen.

For hot forging, sintered specimens were reheated to 1100°C for 25 minutes. The heated specimens were then hot-forged immediately to reduce the specimen height to 2.0 mm (80% height reduction). The table must be arranged as shown in Table 1.
Table 1. Compositions (wt. %) of austenitic stainless steel powders.

| Grade | C   | Si  | Mn  | N   | O   | Ni  | Cr  | Mo |
|-------|-----|-----|-----|-----|-----|-----|-----|----|
| 303L  | 0.016 | 0.85 | 0.10 | -   | 0.24 | 11.40 | 17.70 | -  |
| 304L  | 0.02  | 0.90 | 0.10 | 0.05 | 0.22 | 11.20 | 18.50 | -  |
| 310L  | 0.29  | 1.03 | 0.11 | 0.047 | 0.205 | 20.0 | 24.70 | -  |
| 316L  | 0.02  | 0.85 | 0.10 | 0.04 | 0.20 | 13.0 | 16.80 | 2.20 |

2.2 Characterization and testing
Due to simple specimen geometry, the density of the as-sintered and as-forged specimens was measured by using mass and volume of the specimen. The as-sintered and as-forged specimens were prepared for metallography observation following standard methods. Microstructures were observed by using scanning electron microscopy (SEM) equipped with electron backscatter diffraction (EBSD) to measure grain size and twin boundary fraction.

3. Results and Discussion

3.1 Densities of sintered and forged specimens
Under the same PM process (compaction and sintering), each sintered stainless steel showed different sintered densities the table must be arranged as shown in Table 2. The sintered 316L exhibited the highest sintered density whereas the sintered 303L showed the lowest sintered density. Sintered density results from shrinkage or swelling phenomena during sintering state. In general, sintered austenitic stainless steels gain increased density after sintering [15, 16]. The increased density after sintering relates directly to shrinkage, which is in turn directly proportional to sintered neck size ratio [17]. The sintered neck size or volume depends on contacting areas in powder compacts after cold compaction. Thus, different densification levels in sintered austenitic stainless steels are due to the nature of powder response on compaction action.

Table 2. Properties of sintered and forged austenitic stainless steels.

| Material  | Density (g/cm³) | Porosity (%) | Grain size (µm.) | Twin fraction (%) | Hardness (HV1) |
|-----------|----------------|--------------|------------------|------------------|---------------|
| Sintered 303L | 6.92          | 8.98         | 43.36            | 15.19            | 66.31         |
| Forged 303L  | 7.6           | 0.27         | 12.13            | 3.05             | 308.87        |
| Sintered 304L | 7             | 11.96        | 49.27            | 16.12            | 62.31         |
| Forged 304L  | 7.58          | 2.13         | 12.88            | 3.07             | 351.29        |
| Sintered 310L | 7.1           | 8.64         | 40.77            | 11.34            | 61.18         |
| Forged 310L  | 7.43          | 1.17         | 10.83            | 4.18             | 323.33        |
| Sintered 316L | 6.89          | 11.41        | 44.87            | 13.05            | 69.01         |
| Forged 316L  | 7.7           | 1.03         | 11.47            | 3.16             | 350.57        |

All forged specimens gained increased densities but with different increments the table must be arranged as shown in Table 2. The most density increment was observed in forged 316L. The porosity images in sintered and forged austenitic stainless steels, given as shown in Figure 2. Confirm sintered and forged densities given the table must be arranged as shown in Table 2. The density increment obtained from hot forging is due to metal deformation and flow at high temperatures [18, 19]. Other actions of hot forging on density enhancement are pore closure and bonding [20]. The experimental results implement the hypothesis,
in which density would be increased after hot forging. However, different austenitic stainless steels have different responses to density increase by hot forging.

3.2 Microstructures of sintered and forged specimens
Sintered austenitic stainless steels exhibited equiaxed grains with sizes in the range of 40.0–49.0 µm. There were twins within grains. The twins and pores also existed in forged specimens, except that the forged grains with sizes in the range of 10.0–12.0 µm. The examples of sintered and hot-forged grains as shown in Figure 3.

Figure 2. EBSD Phase map images showing porosity natures of sintered and forged austenitic stainless steels.
3.3 Hardness values of sintered and forged specimens

The hardness values of forged specimens increased appreciably from those of sintered specimens as shown in Table 2 and Figure 4. From the experimental evidences, it is apparently that the significant improvement of hardness is resulted from the increased density and grain refinement.

To find other causes of hardness improvement, the microstructural change regarding twin fraction was examined using EBSD. Quantification of twin fraction was conducted and it found that twin fractions in all forged specimens were lower than those in the respective sintered specimens as shown in Table 2. From this experimental result, the twin fraction has inversely relationship with hardness.
4. Conclusion
Under the same PM processing conditions (compaction and sintering), different sintered austenitic stainless steels showed different sintered densities. It is assumed that the different sintered densities are to differences in compressibility and sinterability of austenitic stainless steel powders. Further improved densities of austenitic stainless steels were obtained by hot forging. The improvement of density led to hardness increase. On the other hand, the grain size and volume fraction of twin were significantly deceased.

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