Powder Metallurgy of M2 High-speed Steel for Rapid Tooling Applications

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Abstract

A rapid tooling method has been developed to make a metallic tooling by powder metallurgy [1]. It is an integration of two techniques: rapid prototyping and powder metallurgy. The main advantages of this rapid tooling technique over the conventional techniques were short production cycle, low investment and manufacture costs. The experiment reported was on the density, microstructure, hardness and shrinkage of M2 high-speed steel parts. The process included de-binding, sintering and tempering of M2 high-speed steel powder. The material used was water atomised M2 high-speed steel powder and was sintered in the temperature range of 1270-1310°C for one hour. The process is typically a liquid phase sintering and enables to obtain high brown densities. After sintering, the micro-structure of the high-speed steel consisted of 6-12% carbides, 15-30 % austenite and 60-80% martensite, and the parts were to be tempered. With sintering at 1300°C and tempering, the results showed that 96% density was obtained, the typical hardness of $Hv_{0.2}510$ (HRc50) was achieved, the horizontal shrinkage of the brown part was controlled at 15%±1% and the vertical shrinkage was at 14%±1%. Sintering above the temperature of 1300°C resulted in increasing of the brown density, rapid growth in grain size and deformation occurred. Based on the combination of density, shrinkage and hardness, the optimal sintering temperature and tempering procedure were determined.

Introduction

In a previous work, a rapid tooling method has been developed to be suitable for making metallic hard tooling by powder metallurgy. It is based on the use of one of the tool steels [1]. In this paper, we have introduced the M2 high-speed steels for this rapid tooling method.

Rapid tooling is the technique to manufacture tooling for injection moulding and die casting quickly and efficiently, and the resultant part will be representative of production material [2]. Rapid tooling methods have received widespread attention, a number of such techniques are commercially available and are being implemented in ever-increasing numbers. Rapid Tooling promises to greatly reduce the lead-time to market for a product. There are many kinds of rapid tooling methods, until now. The most of them are only applicable to short-run production and the high melting point metallic tooling is difficult to produce. Therefore, powder

metallurgy technique was, in this research, adopted to make a rapid metal tooling for medium- or long run production.

Powder metallurgy is a common material processing technique, which constitutes a subdivision of the general metalworking technologies. The advantages and attractions of powder metallurgy originate from several attributes. The ability to shape powders directly into a final component form is a major advantage and the powder metallurgy parts have a more refined and homogeneous microstructure [3, 4]. Powder can be consolidated by many methods and development work has been largely concerned with evaluating the commercial potential of various techniques. Most structural parts are still compacted by linear die pressing and conventional sintering. M2 high-speed steel sintering is based on the liquid phase typically. Unlike solid-state sintering, during the sintering of M2 high-speed steel, the alloy powders are heated to a temperature between the liquidus and the solidus. At this temperature, various amounts of liquid are evident at the grain boundaries, inter-particle boundaries and inside the grains, resulting in capillary forces acting on the semisolid particles, thereby enhancing densification [5].

After the sintering operation, the high-speed steel structure comprises about 15%-undissolved carbides and about 15-30 % untransformed austenite. The parts need to therefore be tempered. The purpose of tempering is to soften the martensite in the usual way, to provide the secondary hardening by precipitation hardening, and to 'condition' the retained austenite by precipitation of carbide so that it can transform to martensite by cooling to room temperature.
As the single -tempered specimen contains up to 20% secondary untempered martensite, a second tempering operation is required in order to relieve the stresses and temper the secondary martensite [6, 7].

M2 high-speed steel densified rapidly, but with a narrow sintering window of about 5ºC. In this study, the experiments were focused on the behaviour of M2 high-speed steels with an aim to establish an optimum sintering and tempering program for rapid metal tooling applications.

Experimental procedure

Production with powder metallurgy (P/M) technology is greatly influenced by a number of critical manufacturing factors. This experiment focused on the density, microstructure, hardness and shrinkage of M2 high-speed steel parts.

Material

Water atomised M2 high-speed steels powder was used in the experiment. The powder particles were mostly round in shape as show in Figure. 1. The mean particle size was about 10 μm; the pycnometer density of the
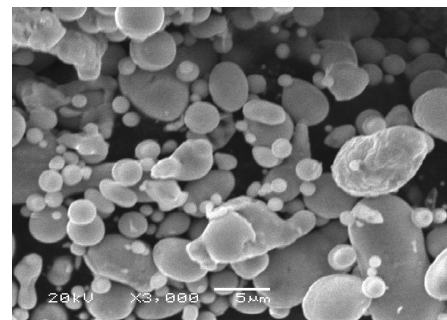

Figure 1. SEM micrograph of M2 powder.

powder was 7.96g/cm^3, with a tap density of 4.61g/cm^3. The compositions (mass %) are listed in table 1.

Table 1 the compositions (mass %) of M2 high-speed steels.

C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Co	V	W	O(ppm)
0.814	0.33	0.26	0.013	0.018	0.02	4.09	5.02	0.07	0.03	1.96	6.26	2060

Processing

The chart below showed that the procedures included the processes started from the product design to the final tooling fitting-up.
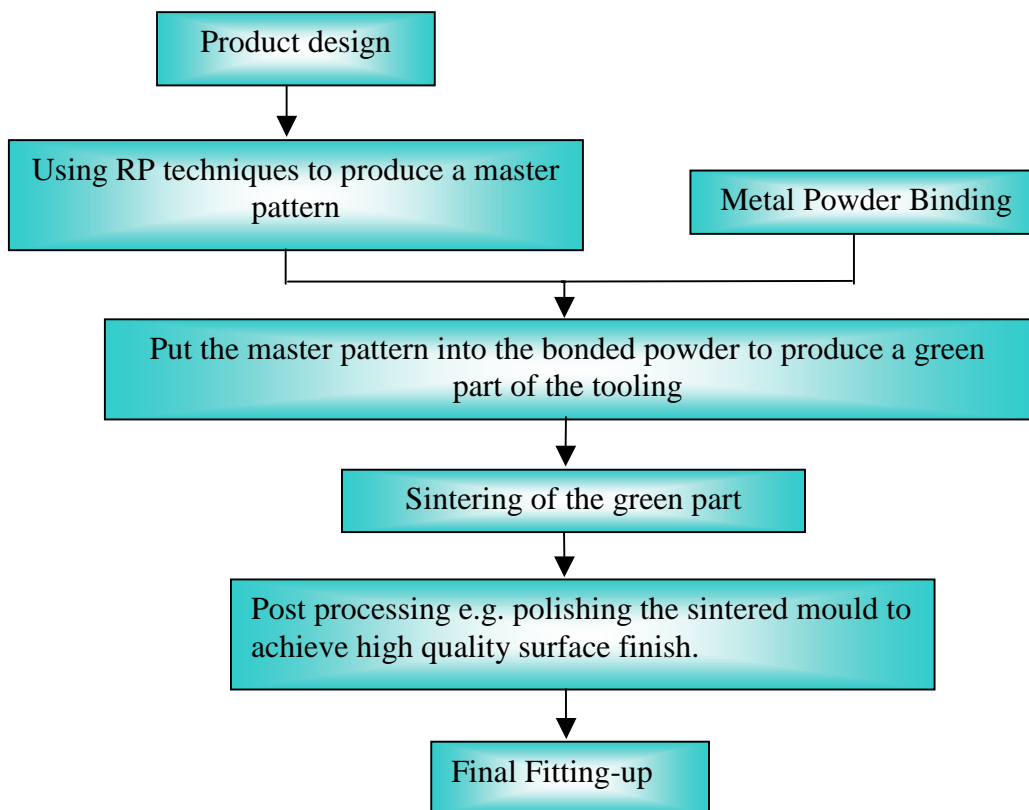
Binder prepare

- Using a solution of 2 %wt polyester and 98 %wt solvent, as binder
- Mixing of 600g powder with the 100g binder

Rapid prototyping

Investment in rapid prototyping systems or their applications can be a big decision to make, because it is very difficult to quantify the advantages (or disadvantages) of factors, e.g., time to market and quality improvements for competitiveness [8]. Considering the requirements

of high accuracy and good surface finish, we chose the SLA RP machine to make the master pattern.

In some cases, there exists a product without the CAD data; silicone molds can be used to mold the master pattern. The process begins with a well-polished master prototype. Liquid silicone and a hardener is mixed and poured into a mold containing the master prototype. After curing in an oven, the master prototype is removed by cutting along the parting line.

Sintering

The sintering experiments were performed in a CM high temperature tube-sintering furnace under argon atmospheres. Sintering was performed at different temperatures to determine the sintering window. Sintering time was 60 minutes, followed by furnace cooling to room temperature.

Tempering

After sintering, the parts need to be tempered. M2 high-speed tool steels often requires tempering at 560–600ºC for 1 hour for two or three times. The tempering experiments were still performed in a CM high temperature tube-sintering furnace under argon atmospheres, as post-heat treatment.

An AccuPyc 1330 Gas Auto Pycnometer was used to determine the density of the sintered parts. The specimens were polished and etched with 4-6% Nital to reveal prior grain boundaries and other microstructure features. The microstructures were observed on an Inverted Microscope Reicaert MEF4M.

Results and discussion

The CAD model was built using Solidworks software. The 3D drawings and rapid prototypes of the master pattern are shown in Figure 2 and Figure 3.
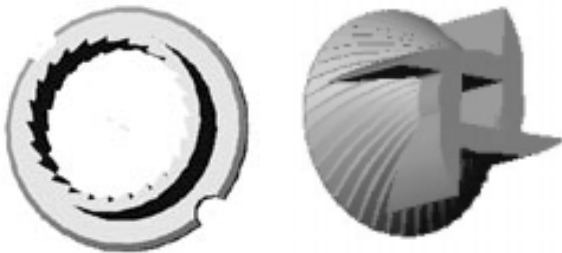

Fig. 2 3-D drawing of the master patterns   Fig. 3 Master patterns fabricated using SLA

Density, shrinkage and microstructure of sintered samples

Figure 4 depicts the density of M2 high-speed steel samples sintered in argon atmosphere for 1 hour. Densification rates at temperatures below 1280°C were consistent with solid state diffusion and were extremely low, but once liquid phase began to appear, the density increased rapidly. In this case, the highest as-sintered density is about 96% theoretical density. It was obtained at the temperature of 1300°C-1310°C.

Shrinkage is one of the key problems. Shrinkage is affected by several factors: a) the type of binder; b) the ratio of the binder in the mixture; c) the solidification time; d) the sintering temperature; e) the type and grain size of powder, etc. The shrinkage affected by a), and b) is relatively lower compare with that affected by the sintering temperature [9]. In our case, the type and grain size of powder do not have much choices. We can only design the sintering cycle to control the shrinkage, and reduce the distortion of products. Figure 5 depicts the shrinkage of M2 high-speed steel samples sintered in argon atmosphere for 1 hour at different temperature, it can be seen that the higher the temperature is, the larger shrinkage will be. This can be explained that the liquid phase volume fraction will be increased with the sintering temperature increase. Sintering above 1300°C led to the formation of excess liquid and resulted in part distortion. Considering the density and shrinkage, 1300°C is the optimum sintering temperature.
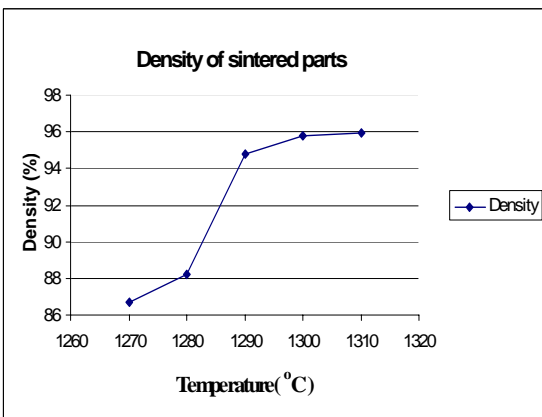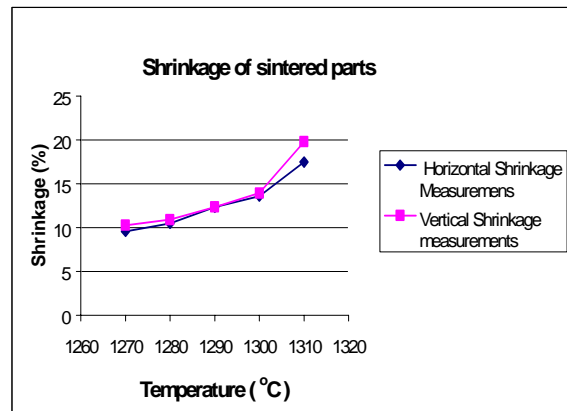

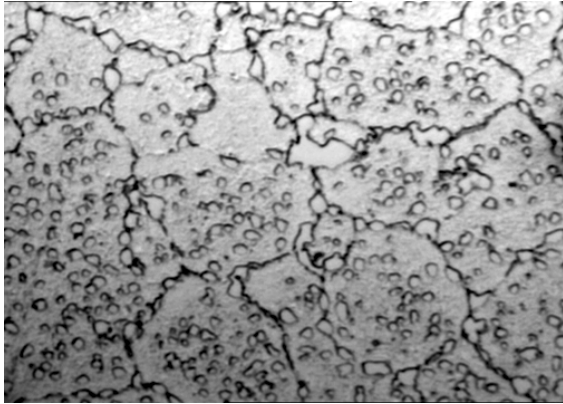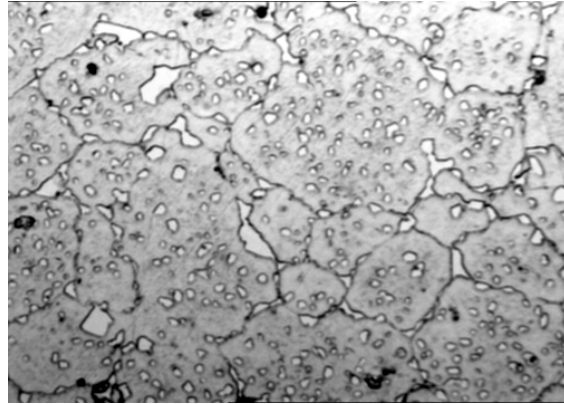Fig. 4 Density of M2 high-speed steel samples

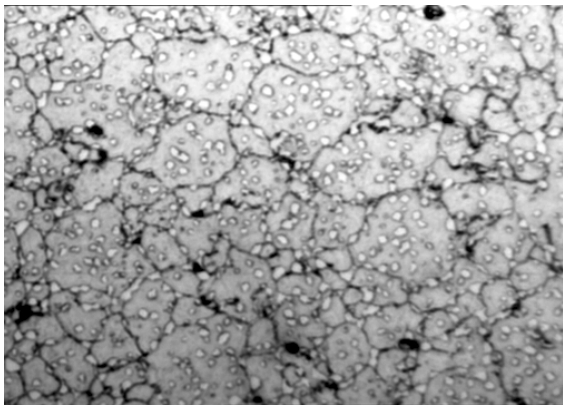Fig. 5 Shrinkage of M2 high-speed steel samples

Figure 6 shows the microstructure of M2 high-speed steel samples sintered at different temperature. For samples sintered at 1270°C, a lot of pores were found in the sintered parts, and liquid phase fraction was very small. This indicated that the part was not sufficiently densified. When the sintering temperature was increased to 1280°C, pores were much fewer, and the liquid phase fraction was a slightly more. At a higher temperature of 1290°C, the pores were smaller and the grain size increases. At 1300°C, the carbides tend to form thick elongated films at grain boundaries and the grain size was much bigger. At 1310°C, the liquid phase fraction were much larger and the grain size was bigger. For a near fully dense and microstructure without grain coarsening, the critical sintering temperature is at 1300°C.
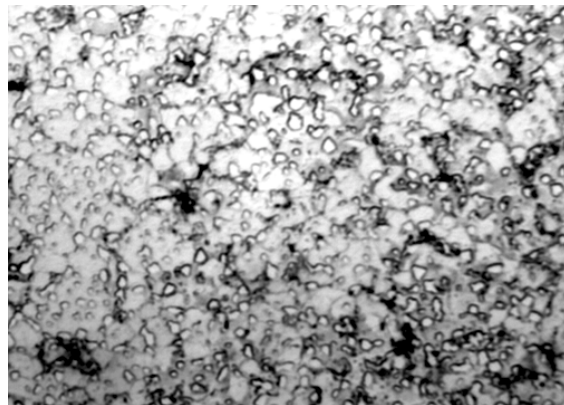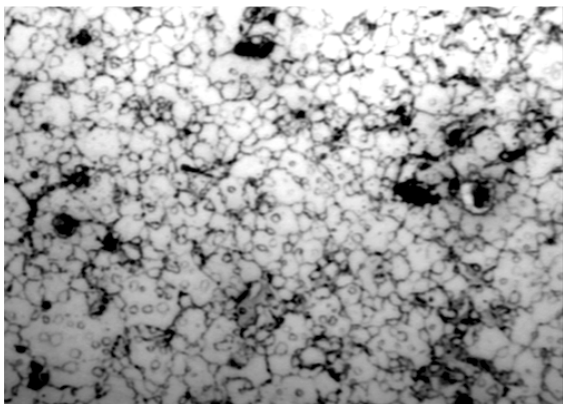
Sintered at 1310°C

Sintered at 1300°C

Sintered at 1290°C

Sintered at 1280°C

Sintered at 1270°C

Fig. 6 Microstructure of M2 high-speed steel samples sintered in argon for 1 hour at different temperature.

Hardness of tempered samples

At room temperature, about 70 to 80% of the austenite is transformed to martensite, so the high-speed steel structure comprises 15 to 30% highly alloyed untransformed austenite and undissolved M_6C and MC carbide (9-12%)[6].

After Sintering, the parts need to be tempered. Tempering is heating of the steel/ martensite with the purpose of below.

- Changing the martensitic structure and towards quasi-equilibrium where ferrite and carbides are formed by nucleation and growth.
- Relieving most of the undesired stresses introduced by sintering,
- To transform retained austenite- if present, - to martensite [10].

High-speed tool steels often requires tempering at 540-600°C for 1 hour for two or three times [6, 7, 11]. The hardness of the M2 high-speed steel samples tempered at the temperature of 580°C is showed in Figure 7. It was found that there was a peak value of hardness for every sample sintered at different temperature. It was because of the precipitation of the secondary carbides. Firstly, due to the precipitation of carbides, they were distributed in the matrix, the hardness value of the sample was increased. Secondly, when the carbide precipitated, the retained austenite was deprived of its alloying elements and its alloying content dropped (carbon and alloying elements partially separated from the austenite during heating at 500°C to 600°C). During the cooling of the high-speed steel samples, the retained austenite, which now has a lower alloy content, was less resistant to transformation and was partially transformed into martensite. The proportion of martensite increased. This in turn made a contribution to the hardness of the material.
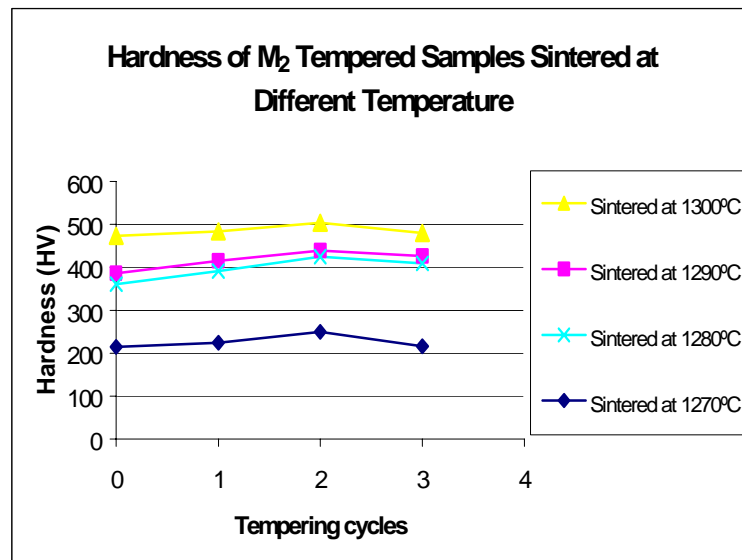

Fig. 7 the hardness of M2 high-speed steel samples tempered at 580°C temperature

After the first tempering, the tooling was having still a considerable quantity of retained austenite, and the martensite formed during cooling is untempered. Therefore it was necessary to repeat the tempering operation to transform this retained austenite to martensite. After second tempering, the precipitation of carbides were sufficient, the maximum hardness value was achieved. During subsequent tempering, the percentage of carbon in martensite decreased as a result, of which the hardness decreased somewhat.

It can be seen that the sintering temperature evident to effect on the initial hardness of high-speed steel samples. Increasing the sintering temperature resulted in increasing the density, and resulted in increased the initial hardness. The higher initial hardness obtained by sintering appeared to persist at all tempering cycles.

Conclusions

1) Different processing parameters, such as sintering temperature, evident to affect the density and shrinkage of M2 steel parts. Increasing the sintering temperature resulted in increasing the liquid phase fraction, the brown density and, at the same time, the shrinkage.

2) According to the combination of density, shrinkage and hardness, the desired results were obtained at the sintering temperature of 1300°C for one hour.

3) During tempering, the content of the carbide precipitated from martensite increases, and as a result, cases the hardness of steel to increases some extent. To attain the maximum secondary hardness it was recommended to temper the sintered M2 steel tool at 560°C to 600°C for two cycles.

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