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Publisher’s version / Version de l'éditeur:
https://doi.org/10.1179/174329007X205055
Powder Metallurgy, 52, 1, 2009-03-01

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Tensile properties of sinter hardened powder metallurgy components machined in their green state

E. Robert-Perron*[1], C. Blais[1] and S. Pelletier[2]

With the increasing demand for sinter hardened powder metallurgy components, there is a growing need to solve the poor machining behaviour that characterises them. Approaches based on green machining appear promising to extend tool life and reduce machining costs. The present study deals with the sintered properties of cylindrical tensile specimens green machined. Results show that tensile properties of components machined in their green state are identical to those of components machined after sintering.

Keywords: Powder metallurgy, Green machining, Sinter hardening, Tensile properties

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Introduction

Powder technologies are provocative to engineers, not only because of the replication capabilities, but because of the design options which allow for the selective placement of phases and pores to tailor the product to the application.[1] The powder metallurgy (PM) process differs from other shaping routes such as precision casting, precision forging, etc., because it necessitates little secondary machining operations.[2] Thus, a discussion about the machining behaviour of PM components may appear as a paradox since the PM process is said to be 'near net shape'. Nevertheless, due in part to the limitations of the process (e.g. the impossibility to generate undercuts in axial pressing) as well as strict dimensional conformance, machining operations are necessary for approximately one-third of the ferrous PM parts produced in North America.[3] Moreover, it is estimated that about 40–50% of all ferrous and steel PM parts made in Europe undergo some machining.[2]

Unfortunately, machining of PM steels is more complicated than that of wrought materials. Compaction, sintering and sintering atmosphere determine the volume fraction of porosity as well as the final microstructure.[2] Therefore, cutting conditions optimised for machining wrought steel cannot be directly applied to PM components even if both series of parts present the same chemistry and microstructure. The mediocre machining performances of PM components are usually attributed to the interrupted cutting and lower thermal conductivity that are inherent to porous materials.[4,5] Moreover, the usage of sinter hardenable powders allows manufacturers to harden parts during the last stage of the sintering cycle by adequately controlling the cooling rate obtained by forced convection. By using the latter approach, no secondary heat treating operation is necessary to obtain the harder and/or tougher microstructures required. This proves as a tremendous advantage since it significantly reduces production costs while eliminating the usage of quenching media that are detrimental to the environment. On the other hand, such microstructures make the components harder to machine leading to accelerated cutting tool wear and increased production costs, which tend to counterbalance the gains obtained with sinter hardenability.

A new approach to solve the low machining performances associated with sinter hardened PM steels is green machining, i.e. machining before sintering. Indeed, the strong atomic bonds that exist between particles of sintered parts, as well as hard and/or though phases (martensite and/or bainite), have not yet been formed at this stage of the manufacturing process. Therefore, the mechanical properties of green compacts come only from the mechanical interlocking and the cold welding between neighbouring particles. Green machining is not a straightforward procedure since steel parts pressed to a green density of 6·8 g cm^{-3} have typical green strength values of 12–17 MPa (about 1750–2500 lb in^{-2}). These values are insufficient to allow proper holding of the parts in the chuck of a lathe or a machining centre and would lead to catastrophic failure during machining.[2,6] Recent developments in binder/lubricant technologies have led to high green strength systems that enable green machining. These polymeric systems are even more effective after a curing treatment in air at low temperature (ex. 190°C) during which a strong polymeric network is formed and strengthens the green parts.[7] Final green strength >35 MPa (5000 lb in^{-2}) are obtained with these systems, which secure clamping during machining. Such components have been successfully machined in their green state, in terms of surface finish and average width of breakouts, either for drilling or turning operations.[6,8,9] However, even if PM components with

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Published by Maney on behalf of the Institute
Received 30 October 2006; accepted 19 February 2007
DOI 10.1179/174329007X205055

satisfactory geometrical quality have been produced by green machining, to our knowledge, no study concerning the sintered properties of such components has been published. Thus, in order to make green machining a viable manufacturing process, there is a need for the PM industry to characterise the mechanical properties of sintered components produced using a green machining operation. The objective of the present paper is to compare the sintered tensile properties of cylindrical specimens machined in their green state with other machined after sintering. Tests were performed for a sinter hardened powder mix with improved mechanical properties.

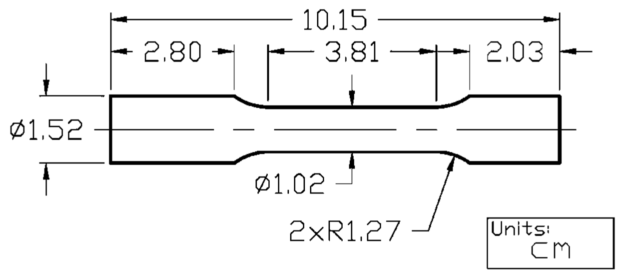
Experimental

Material investigated

A powder system was produced based on Quebec Metal Powders Ltd 4601 sinter hardenable powder (Fe–1·8 wt-%Ni–0·5 wt-%Mo–0·2 wt-%Mn), to which 2·0 wt-%Cu and 0·6 wt-%C were added. The latter premix follows the denomination FLC-4608 based on MPIF Standard 35.[10] Lubrication was conducted using 0·65 wt-% of a proprietary binder/lubricant (FLOMET HGS) specifically adapted for applications where high green strength is required.[11] This mix was pressed into rectangular plates (10·8 × 10·8 × 2·5 cm) to a green density of 7·00 g cm^{-3}. The plates were then submitted to a curing treatment in air at 190°C for 1 h to increase their green strength from 21 (3050) to 52 MPa (7575 lb in^{-2}), as measured following MPIF Standard 15.[12] The cured plates were sliced in four rectangular bars (2·5 × 2·5 × 10·8 cm).

Samples preparation

A first series of specimens were produced by machining cured rectangular bars into cylindrical tensile specimens. Figure 1 presents the geometry of the tensile specimens used in the present study. The samples were not symmetrical to ensure proper holding in the jaws of the lathe during machining. The green machining operation was performed using a Mazak Nexus 100 CNC lathe at a surface speed of 122 m min^{-1} and a feedrate of 0·0254 mm rev^{-1}. Tool holder SCLCR102 and cutting tool CPMT060204FW (produced by Kennametal) were used. These cutting parameters were selected based on the results of a previous research that showed that, for the type of powder mix characterised in the present study, they optimise green machining, i.e. they minimise particle pull out while maximising the surface finish.[9] A second series of tensile specimens was obtained by machining sintered rectangular bars. The latter series of rectangular bars was sintered along with the cylindrical tensile specimens machined in their green state in a belt furnace in an atmosphere of 90%N_2–10%H_2 at 1120°C for 25 min and rapidly cooled (global cooling rate: 1·5°C s^{-1} from 650 to 400°C) to transform



1 Cylindrical tensile specimen used for characterising sintered properties of green machined PM steel

the austenite into a mixture of martensite and bainite. The sintered bars were then machined into cylindrical tensile specimens having the same dimensions as those machined in their green state. The machining of the sintered specimens was performed using parameters optimised for the material studied as found in the literature.[2,13] The cylindrical tensile specimens machined in their green state had a cross-section of 0·82 cm^2 while that of the rectangular bars was 6·25 cm^2. Therefore, even if both series of specimens were sintered and fast cooled simultaneously, heat transfer is accelerated in components machined in green state since they present a smaller cross-section. Therefore, the local cooling rate into the heart of the components differed for the two series of specimens and so did the microstructures as well as the mechanical properties.

Therefore, a third series of specimens was necessary to compare only the influence of the surface finish on the sintered tensile properties of components green machined with others machined after sintering. This series was green machined from cured rectangular bars to a diameter of 1·07 cm, i.e. 0·05 cm larger than that of the final size of the tensile specimens (Fig. 1). These samples were sintered under the conditions described above. A second machining operation was then performed after sintering to bring the specimens to the same dimensions as those from the other two series. Therefore, using identical sintering parameters as for other series, this third series of samples was cooled using the same local cooling rate into the heart of the components as the parts machined in their green state, thus yielding the same microstructure. Finally, the three series of sintered tensile specimens were tempered at 200°C for 1 h. The tensile tests were performed using a universal testing machine (Instron, model T20000) using a crossbar velocity of 1 mm min^{-1}.

Results and discussion

Table 1 presents the tensile properties measured on the three series of specimens. It can be seen that the mechanical properties of samples machined in their green state are significantly higher than those of components machined after sintering (columns 3 and 4

Table 1 Tensile properties

Properties	Machined in green state	Machined after sintering	Machined after sintering (premachined in green state)
Hardness, HRC	33 ± 1	28 ± 1	33 ± 1
Yield strength, MPa	940 ± 12	794 ± 24	950 ± 20
Ultimate strength, MPa	980 ± 36	900 ± 4	1028 ± 22
Ductility, %	1·08 ± 0·04	1·25 ± 0·14	1·14 ± 0·04

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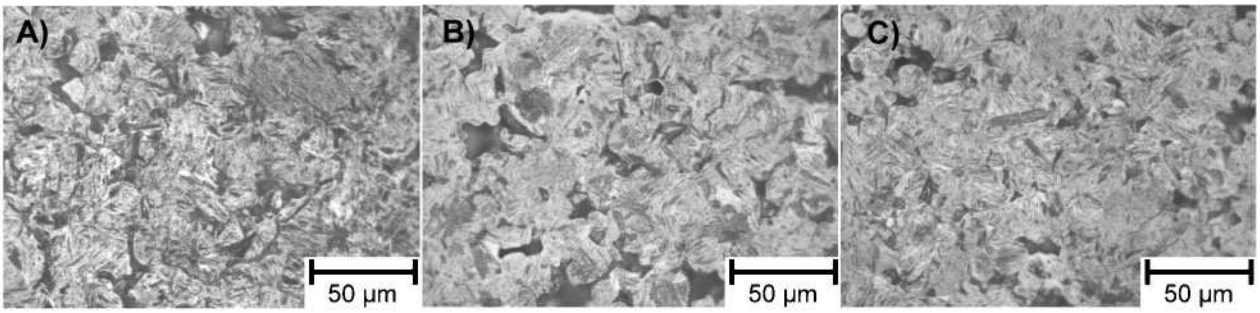


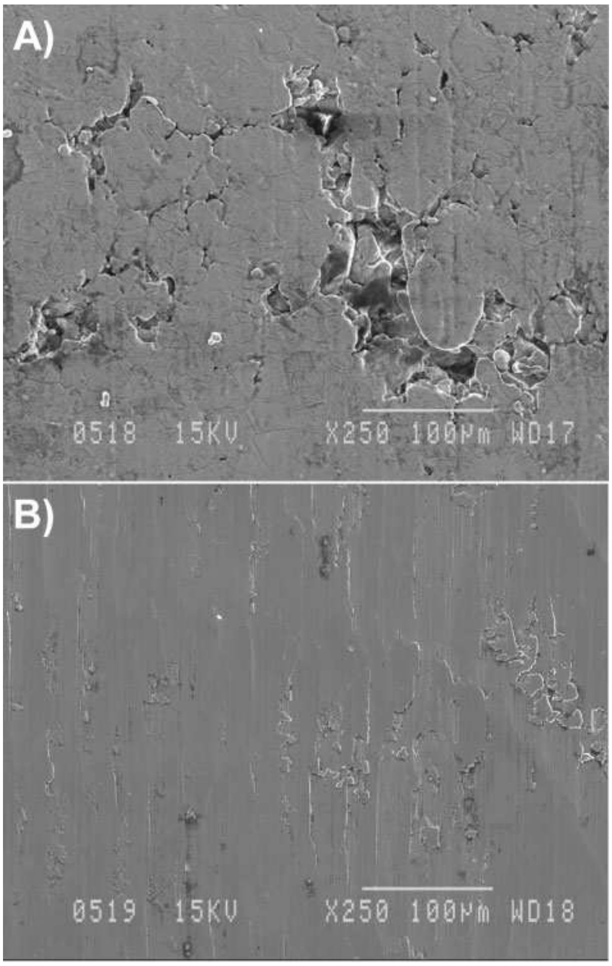
A – green machined; B – machined after sintering; C – machined after sintering

2 Typical microstructures: premachined in green state; etching nital 2 vol.-%

in Table 1). Yield and ultimate strengths of specimens machined in their green state are respectively 18 and 9% higher than those of specimens machined after sintering. These results are explained by the harder microstructure (tempered martensite: 33 HRC) characterised on samples green machined while a mix of tempered martensite and bainite (28 HRC) is found on samples machined after sintering, as shown in Fig. 2*a* and *b*. Differences in microstructure stem from the different local cooling rates in the heart of the specimens during the last stage of the sintering cycle. Thus, the green machining process has the advantage of producing components with the desired microstructure and hardness, which is not always the case when components are machined after sinter hardening since it may happens that areas with harder microstructures are removed during machining.

A third series of samples was used to compare the influence of the surface finish on the tensile properties between specimens machined in their green state and others machined after sintering. The latter series of samples yielded the same microstructure (tempered martensite) as components machined in their green state due to the identical cooling rate in the components, as seen in Fig. 2*a* and *c*. As expected, the apparent hardness of these two series was also identical, as shown in Table 1. Tensile properties (yield strength, ultimate strength and ductility) of components green machined are within 5% lower than those of components machined after sintering (premachined in green state) (*see* columns 3 and 5 in Table 1). However, considering standard deviations, these differences are not significant. Thus, for the same microstructure, the mechanical properties of sintered components machined in their green state are identical to those of components machined after sintering. Moreover, based on the sintered properties, no crack or microcrack formation was initiated during green machining or handling of the green PM tensile specimens. Indeed, if this would have happened, the sintered properties would have been lower than those of components machined after sintering.

Surface finish R_a, which is the arithmetic mean of the absolute values of the profile deviation from the mean line, was measured using a profilometer (Mitutoyo, model SJ-201P).[14] Surface finish R_a of 1·43 and 0·17 μm was respectively measured on components machined in their green state and components machined after sintering. Figure 3*a* shows a typical surface finish of components machined in their green state while Fig. 3*b* shows the surface finish of specimens machined after sintering. It can be seen in Fig. 3*a* that the particles were cut during green machining. However, very low particle deformation occurred leaving the porosity opened, which explains the rougher surface finish measured on specimens machined in their green state. This latter result also indicates that, contrary to specimens machined after the sintering cycle, green machined PM components can be steam treated after machining. Indeed, conventional steam treatment of PM components requires that the surface pores be opened for the adequate formation of an adherent oxide layer.[1] Therefore, if machining is required, it has to be performed after the steam treatment otherwise the surface porosity is closed as highlighted in Fig. 3*b*. This latter situation implies that the cutting tool has to



A – component machined in green state; B – component machined after sintering

3 Surface finish characterised using scanning electron microscope

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cut through the oxide layer, which decreases drastically the cutting tool life. In the case of samples green machined, the surface porosity is left opened making it possible to perform the steam treatment after the final geometrical features have been incorporated through machining operations.

Conclusions

The present study compares the sintered tensile properties of cylindrical specimens either machined in their green state or machined after sintering. The main findings of the present research can be summarised as follows.

1. It has been shown that specimens machined in their green state present higher mechanical sintered properties than components machined after sintering. This is due to the higher local cooling rate into the heart of the components during the last stage of the sintering cycle than that of components machined after sintering, which results in harder microstructure. Therefore, green machining has an advantage on the machining of sinter hardened PM components after sintering. Green machining not only reduces tool wear but also produces, for identical cooling rate in the furnace, components with harder microstructure and higher mechanical properties. Moreover, based on the sintered properties of components machined in their green state, green machining did not initiate cracks or microcracks formation and neither did the handling of the specimens from the lathe to the sintering furnace.

2. For the same microstructure, mechanical sintered properties of PM components machined in their green state are identical to those of parts machined after sintering. Therefore, the rougher surface finish observed in green machining does not significantly affect the tensile properties of such specimens.

3. Because green machining leaves the surface porosity opened, it permits steam treatment of the components after the machining operations are performed. This prevents having to machine through the oxide layer formed on the surface of the components as it is the case for components that are not green machined.

Acknowledgements

The authors wish to thank Dr Sylvain St-Laurent from Quebec Metal Powders for the fruitful discussions as well as Dr Leander F. Pease III for compaction and sintering.

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