DEVELOPMENT OF EASY-MACHINABLE STAINLESS STEEL POWDER FOR MANUFACTURING SINTERED STAINLESS COMPONENTS

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ABSTRACT

Stainless steels offer excellent corrosion resistance compared to other ferrous steels such as plain-carbon and low-alloy steels. Owing to their carbon and high alloying content, stainless steels are usually difficult to machine as they become gummy and work harden during machining. Since the machinability behavior of stainless steels is very different, machinability enhancers that work for other ferrous steels do not always have the same effect in stainless steels. Current additives such as MnS and MoS_2 offer marginal improvement in machinability, while severely decreasing corrosion resistance and also are prone to decomposition if sintered in reducing atmosphere.

Research efforts have been made in developing an easy-machinable version of stainless steel powder using powder manufacturing technology. This paper presented the results obtained on the newly developed 300 series easy-machinable stainless steel powders. The newly developed 300 series materials were found to have identical green and sintered properties to their standard grade counterparts while offing greater machinability without deteriorated effect on corrosion resistance.

INTRODUCTION

As a near-net shape technology, powder metallurgy (PM) provides significant benefits in minimizing material and energy waste by eliminating or reducing secondary operations such as machining compared to other manufacturing technologies.[1] However, machining operations are still required for a large portion

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of PM components to achieve desired dimensional tolerances and surface finish. Compared to wrought steel, PM materials are generally considered difficult to machine due to internal porosity and interrupted cutting leading to inconsistent machining and unpredictable tool failure. Even within PM materials, the machinability can be very different depending on microstructure and hardness of material system.[2]

Stainless steels contain high percentages of chromium and other alloying elements, typically 18%Cr and 12%Ni in 300 series, to provide excellent corrosion resistance compared to other ferrous steels such as plain carbon and low-alloy steels. Carbon is generally a prohibited element in stainless steel as it can deteriorate corrosion resistance by formation of deleterious chromium carbide.[3] As a result, stainless steels are relatively soft materials and the machinability behaviors are very different from plain carbon and low-alloy steels. They are usually difficult to machine as they become gummy and work harden during machining. The austenitic grades (300 series) are not as machinable as the ferritic grades (400 series), due to the fact that the austenitic grades contain much higher amounts of alloying elements which causes them to work harden readily during machining.[4]

To improve the machinability of stainless steels, manganese sulfide (MnS) is commonly used as a machinability enhancer; however it doesn't provide the improvement as effective as it does for plain carbon and low-alloyed steels. Furthermore, the addition of MnS to stainless steel results in a severe decrease in the corrosion resistance.[5] Another common solution for improving the machinability of stainless steel is to impregnate resin in sintered components to seal the porosity, reduce heat generation during machining, and eliminate interrupted cutting action. Resin impregnation not only greatly increases operation cost but also lacks consistency in improving machining due to density gradients in the components which result in variation of the resin impregnation process. Therefore, the improvement in machining of stainless steels remains a challenge for the industry and effective solutions are desired to improve the machinability in a cost-effective way without deteriorating corrosion resistance.

Stainless steel powder is generally made by water-atomization of molten virgin metal and alloys, followed by sizing and mixing processes to provide desired material properties and performances of sintered components.[6] Due to its high alloy content and normally being used in as-atomized condition, stainless steel powder is rather less compressible compared to plain carbon and low-alloyed steels. Research efforts have been made in developing an easy-machinable version of stainless steel powder grades, called SS-EZ grade, using powder processing know-how and proprietary processes. In order to improve the compressibility and to increase the green strength, a new lubricant system was also designed for the SS-EZ grade. The goals of this development are to provide a higher compressible and easy to machine stainless steel powder grades for manufacturing sintered stainless components.

This paper presents the results obtained on the newly developed 300 series easy-machinable stainless steel powders (designated EZ). Machinability, green and sintered properties, and corrosion resistance of the newly developed 300 series materials are compared with those of their standard grade counterparts.

EXPERIMENTAL PROCEDURE

Materials

The newly developed 300 series easy-machinable stainless steel powders, designated here as 304L-EZ and 316L-EZ, were prepared to achieve identical alloying contents to standard 304L and 316L stainless steel powder grades (North American Höganäs High Alloys). These powder grades were produced by water atomization and had a nominal particle size of –100 mesh (<150μm). Table 1 lists the typical alloyed elements and amount contained in normal 304L and 316L stainless steel powders. For test sample preparation, 1% lubricant was used in each case to make ready-pressed premixes (Table 2).

Table 1: Typical Alloyed Elements and Amount Contained in 304L and 316L SS Powder

Grade	%Fe	%Cr	%Ni	%Mo	%Si	%Mn	%C
304L	Bal.	18.5	11.2	-	0.8	0.14	0.02
316L	Bal.	16.8	13.0	2.2	0.8	0.12	0.02

Table 2: Stainless 300 Series Premixes Used in This Study

Premix ID	Description
304L **304L-EZ**	Standard 304L grade +1% Li-St Newly developed easy-machinable 304L grade +1% new lube
316L **316L-EZ**	Standard 316L grade +1% Li-St Newly developed easy-machinable 316L grade +1% new lube

Two types of test specimens were prepared for this study. The premixes were compacted into transverse rupture strength (TRS) bars at compaction pressures of 552 MPa (40 tsi) and 690 MPa (50 tsi) for determination of compacting properties, sintered properties and corrosion resistance.[7] For machinability tests, the premixes were compacted into ϕ55 x ϕ35 x 20H mm rings (~186 g) at a green density of 6.4 g/cm^3.

Except where specified, the TRS test bars were sintered in a laboratory batch furnace at 1177 °C (2150 °F) for 30 minutes in an atmosphere of 100% v/o hydrogen with a normal cooling rate (<0.5°C/sec). The ring specimens were sintered in a production pusher furnace at 1288°C (2350 °F) for 30 minutes in an atmosphere of 100% v/o hydrogen with a normal cooling rate (<0.25°C/sec).

Material Property Testing

For the premixed powders and compacted specimens, apparent density and flow rate, green strength and green density were determined in accordance with MPIF Standards 02, 04, 15 and 45 respectively.[7] Sintered TRS specimens were used for measurement of apparent hardness, dimensional change, sintered density and transverse rupture strength in accordance with MPIF Standards 41, 42, 43, 44 respectively. Microstructure evaluation was conducted on the machined ring specimens.

Corrosion Testing

The as-sintered transverse rupture strength (TRS) test bars were used for corrosion tests. For each material, six replicate TRS test bars were subjected to the test. The tests were performed by immersion in a neutral, 5% sodium chloride solution, in accordance with ASTM Test Method B 895-05.[8] Test specimens were placed in individual glass jars (closed top) containing the test solution with a layer of 3 mm (0.1 in) diameter glass beads at the bottom of the jars. The specimens were examined periodically for evidence of corrosion (stain or rust). Observations were recorded in accordance with the scale presented in Table 3.

Table 3: Corrosion Testing Rating Criteria

Rating	Description
A	No sign of rust or stain
B	Up to 1% of specimen surface covered with rust or stain
C	Up to 25% of specimen surface covered with rust or stain

For each specimen, the elapsed time from the beginning of the test until a rating change was determined. The corrosion tests were aborted after 1000 hours.

Machinability Tests

Machinability testing was performed by a turning test since it is relatively consistent and easy to monitor tool wear compared to a drilling test. Ring specimens were subjected to inner diameter (ID) turning with a NC machine at Farzati Manufacturing (Greensburg, Pennsylvania). A TiCN coated insert made by Iscar was used for the ID turning. The machining was conducted in the wet condition with a water based coolant (5% Hocut 795 AS) at a consistent cutting speed. The test parameters are listed in Table 4.

Table 4: Parameters for Machinability Tests

Parameter	Condition A	Condition B
Cutting speed	457 m/min (1500 sfm)	549 m/min (1800 sfm)
Feed rate	0.1 mm/rev (0.004 in/rev)	
Depth of cut	0.5 mm (0.02 in)	
Length of cut	20 mm (0.8 in)	

Machinability was evaluated by measuring the insert wear after a certain machining distance using a Hitachi S-2600N scanning electron microscope. The insert then resumed machining. This procedure was continued until the testing was terminated. A depiction of the wear measurement technique is shown in Figure 1.

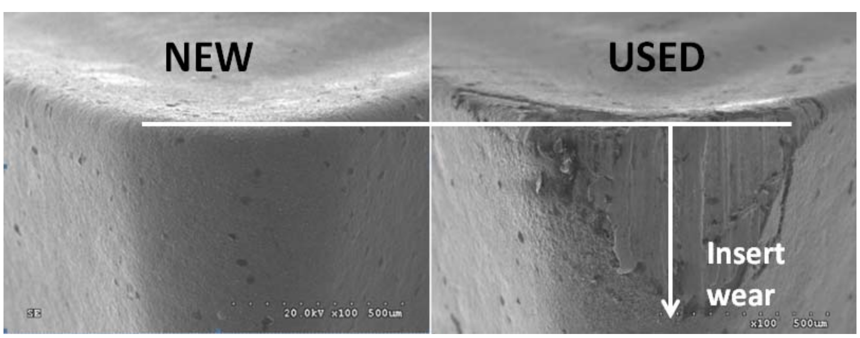


Figure 1. Insert wear measurement technique

RESULTS

Compacting and Sintered Properties

The green properties of 304L-EZ and 316L-EZ powders are shown in Table 5 along with those of standard 304L and 316L powder. Both of the SS-EZ grades have very similar apparent density and slightly better flowability compared to the standard grades. Even though the compressibility of the SS-EZ grades with 1%new lube is identical to the standard grades with 1%Li-St, the new lubricant system designated for the SS-EZ grades significantly increases the green strength by more than 25%. Higher green strength is beneficial to prevent green state cracks as stainless steel powder has poor compressibility and is often not able to achieve a high green density for components as compacted.

No noticeable differences are found in the sintered properties of these materials, as shown in Table 6. The carbon and nitrogen contents of the sintered materials were found to be very similar. The SS-EZ materials have very similar sintered strengths and hardness compared to the standard grades. The dimensional change of both SS-EZ grades are very close to those of their standard grade counterparts.

Table 5: Compacting Properties of the Test Premixes

Property	**304L**	**304L-EZ**	**316L**	**316L-EZ**
Apparent density, g/cm^3	2.90	2.92	2.94	2.94
Flow rate, sec/50g	34	31	32	29
Green density, g/cm^3				
at 552MPa (40 tsi)	6.49	6.46	6.55	6.53
at 690MPa (50 tsi)	6.67	6.65	6.75	6.71
Green strength, MPa (psi)				
at 552MPa (40 tsi)	5.0 (730)	6.3 (920)	5.1 (740)	6.6 (960)
at 690MPa (50 tsi)	7.8 (1100)	9.6 (1390)	7.0 (1020)	8.9 (1290)

Note: 304L and 316L were lubricated with 1.0% Li-St while 304L-EZ and 316L-EZ were lubricated with 1.0%new lube.

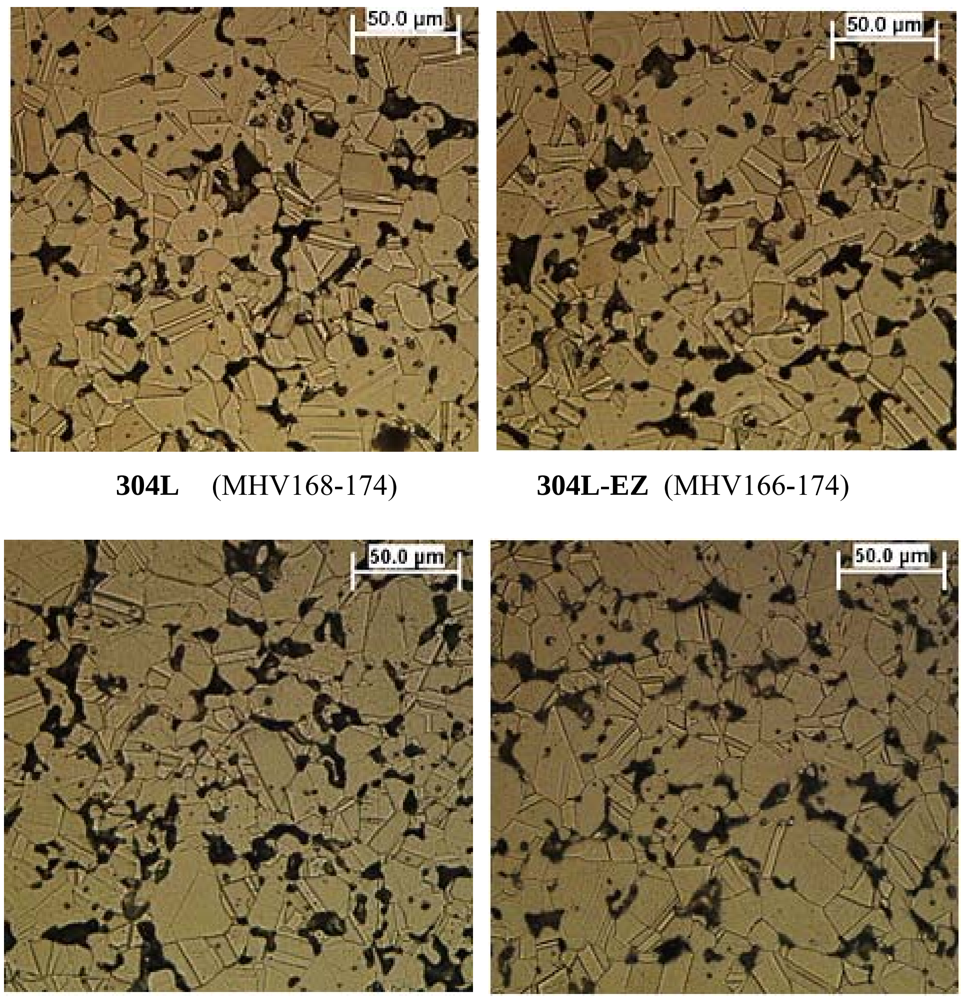
Table 6: Sintered Properties of the Test Premixes

Property	**304L**	**304L-EZ**	**316L**	**316L-EZ**
Sintered density, g/cm^3	6.60	6.58	6.66	6.63
Carbon content, %C	0.040	0.044	0.040	0.039
Nitrogen content, %N	0.024	0.025	0.018	0.022
Transverse rupture strength, MPa	719	722	740	707
(x 10^3 psi)	(104.3)	(104.7)	(107.3)	(102.6)
Hardness, HRB	35	36	35	36
Dimensional change, %	-0.56	-0.56	-0.57	-0.56

Note: all samples were compacted at 40 tsi and then were sintered at 1177°C (2150°F) for 30min. in 100%v/o H_2

Microstructure

The sintered ring specimens that were used for machinability tests were selected for microstructure analysis. The results are shown in Figure 2. All of the materials exhibited a well sintered austenitic structure with twining bands. No differences in microstructure can be observed between the SS-EZ grades and their standard grades. For microhardness (MHV) of matrix obtained from microindentation test, the SS-EZ materials have similar values to their standard grades. However, the matrix of 316L materials is slightly harder than that of 304L materials. This increased microhardness is the result of the additional 2%Mo contained in the 316L stainless steel. The difference in microhardness could not be detected in apparent hardness where the 316L steel has identical apparent hardness to the 304L steel.



304L (MHV168-174) **304L-EZ** (MHV166-174)

316L (MHV189-208) **316L-EZ** (MHV192-206)

Figure 2. Microstructures of test materials after sintered at 1288°C (2350°F) in 100%H_2 for 30min (Glyceregia etched)

Corrosion Resistance

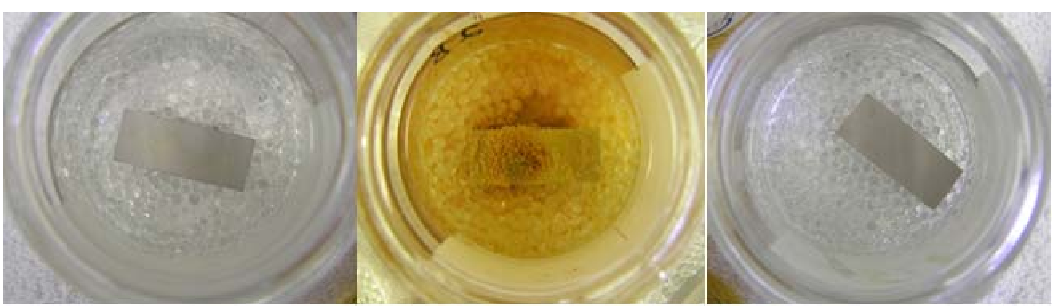
The corrosion resistance of 316L and 316L-EZ material was evaluated by immersion in 5%NaCl solution. The results are shown in Table 7. For each material, a total of 6 TRS test bars were used. For comparison, the 316L+0.3%MnS material was also included in the testing. Figure 3 and Figure 4 show the corrosion status of test bars after immersion for 576 hours (24 days) and 1008 hours (42 days), respectively.

As expected, the 316L material containing 0.3%MnS started to rust within 24 hours and all of test bars reached "C" rating after 24 hours. Similar results were reported in literature for 316L material containing 0.3%MnS.[9] For 316L standard material, two test bars developed stains on the surface after 24 and 192 hours respectively while the remaining four test bars remained in "A" rating (no rust or stain) even after immersion in the salt solution for 1008 hours (42 days). The 316L-EZ materials exhibited similar corrosion resistance as the standard grade 316L, except for one test bar which started to rust after 72 hours. This appears to have been caused by powder contamination based on the appearance of the rust spot. The remaining four test bars remained in the "A" rating for 1008+ hours (42 days) after they immersed in the salt solution. The corrosion test results demonstrate the newly developed SS-EZ material performed in the same manner in corrosion resistance as the standard material.

Table 7: Results of the Corrosion Tests

Material	316L		316L-EZ		316L +0.3%MnS	
Corrosion Resistance	hours	# of bars	hours	# of bars	hours	# of bars
"A" rating	1008+	(4)	1008+	(4)	6	(6)
"B" rating	1008+	(2)	1008+	(1)	12	(6)
"C" rating	--	--	240	(1)	24	(6)

Note: total 6 test bars were tested for each material, sintered for 30 minutes at 1288 °C (2350°F) in 100% H_2



316L **316L+0.3%MnS** **316L-EZ**

Figure 3. Corrosion status of specimens immersed in 5 wt%NaCl solution for 576 hours

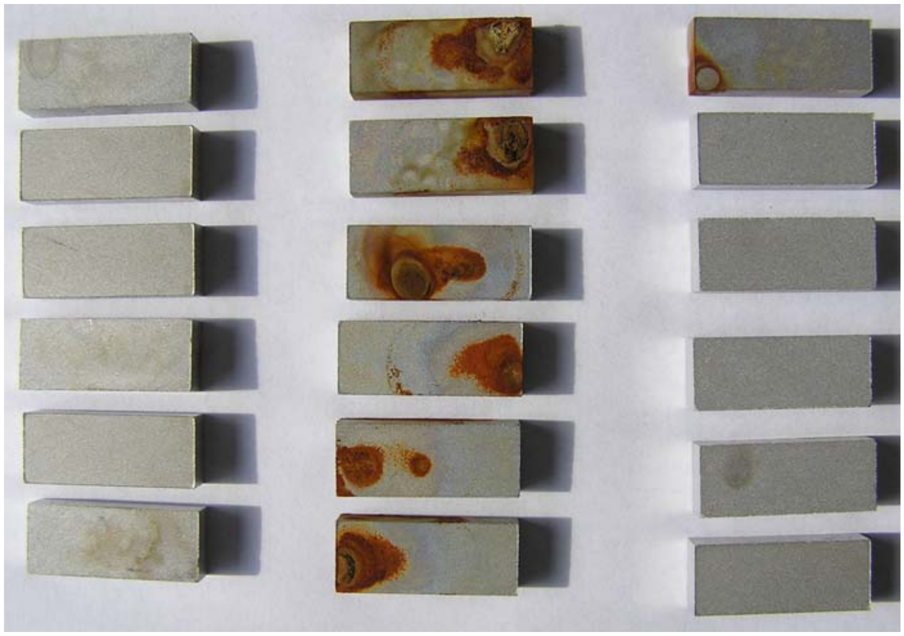


Figure 4. Corrosion status of specimens after immersed in 5%wt NaCl solution for 1008 hours

Machinability Evaluation

Inner diameter (ID) turning was employed to determine relative machinability of the 300 series stainless materials. Machining was performed in the wet condition with a water based coolant. In order to create tool wear using limited test rings, the tests employed cutting speeds that were much higher than the speed recommended for the type of inserts.

Figure 5 shows the tool wear measured after cutting the 304L and 304L-EZ ring specimens for various passes at different cutting speeds. At a cutting speed of 549m/min (1800sfm), the normal 304L material could only be cut for 60 passes before the tool wear exceeded the benchmark of 200 µm. Excessive wear occurred after cutting the normal 304L material for 90 passes. In contrast, the 304L-EZ material could be cut for 90 passes with the tool wear still kept at a minimal level. When the cutting speed was reduced to 457m/min (1500sfm), in the case of normal 304L, the tool life was extended to 210 passes but it failed after cut 240 passes. Under the same conditions, the 304L-EZ material machined more easily than its standard counterpart. Small initial tool wear was observed after cutting the 304L-EZ for 240 passes. For comparison, the wear status of inserts after cutting 304L and 304-EZ materials for the same passes at different cutting speeds is shown in Figure 6.

For 316L and 316L-EZ materials, similar differences in machinability were observed. As shown in Figure 7, the normal 316L material caused the tool failure after it was cut for 90 passes at a cutting speed of 549m/min (1800sfm), and 330 passes at a cutting speed of 457m/min (1500sfm) respectively. In contrast, the 316L-EZ material could be cut for 90 passes and 330 passes respectively under the same conditions without tool failures. The wear status of inserts after cutting 316L and 316-EZ materials for the same number of passes at different cutting speeds is shown in Figure 8.

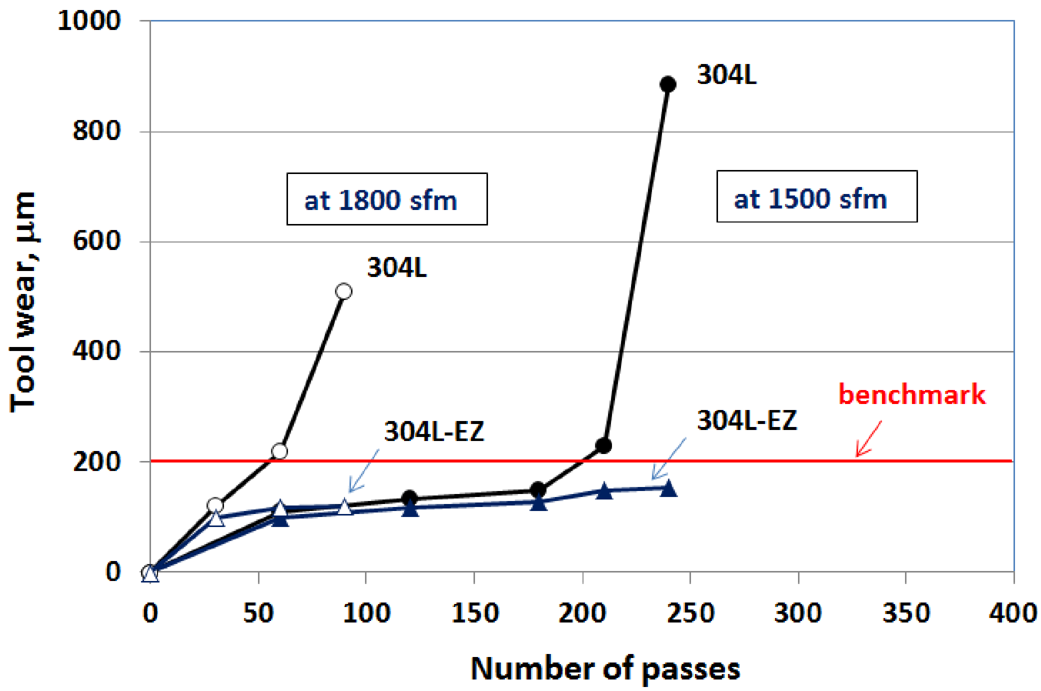


Figure 5. Comparisons of tool wear –304L and 304-EZ materials

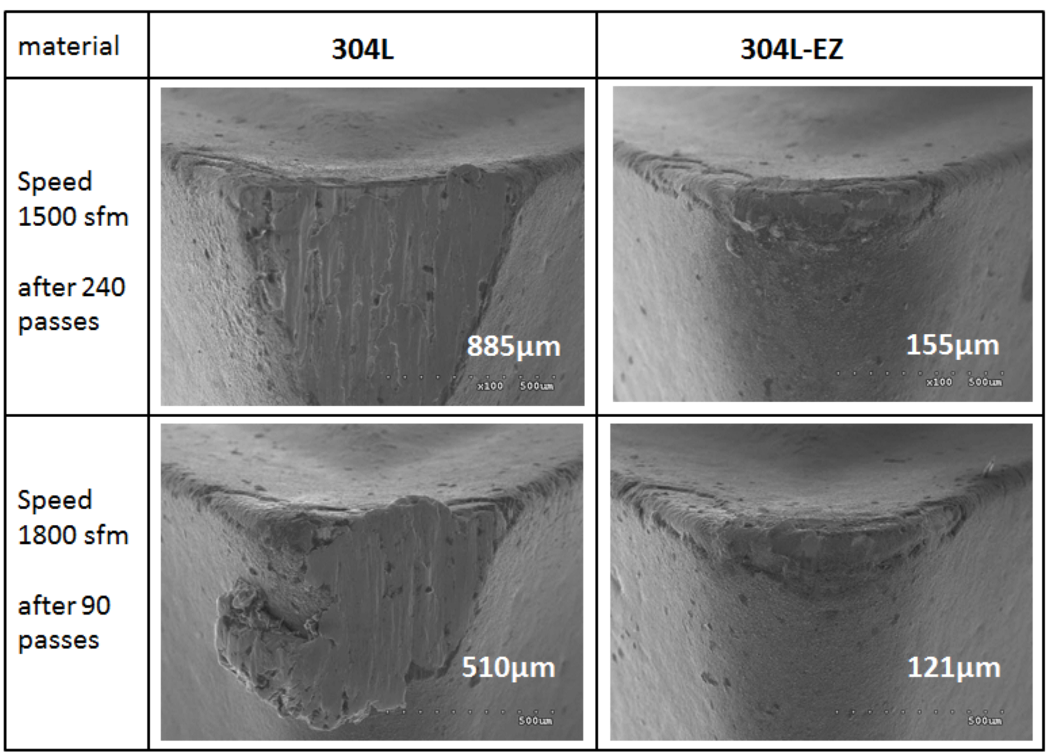


Figure 6. SEM photographs of insert wear status – 304L and 304-EZ materials

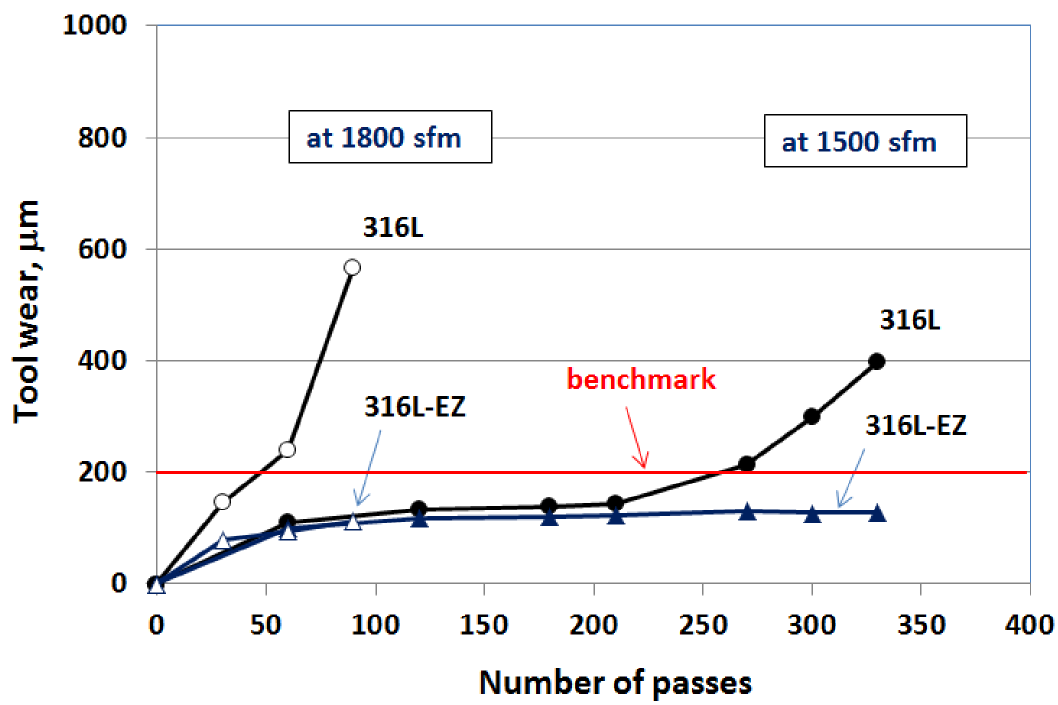


Figure 7. Comparisons of tool wear –316L and 316-EZ materials

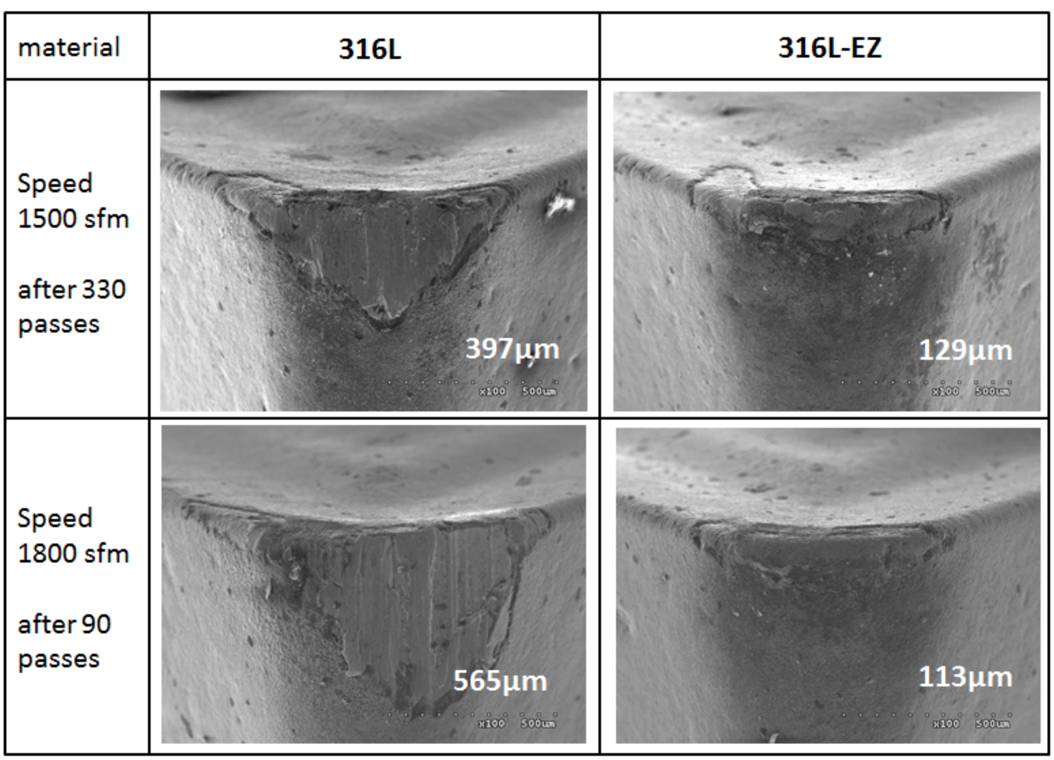


Figure 8. SEM photographs of insert wear status – 316L and 316-EZ materials

DISCUSSION

The stainless steel EZ grades showed similar sintered properties and corrosion resistance to their standard grade counterparts. One important difference between the standard and EZ grades was the improvement in powder properties, specifically flowability and green strength. Improving the flow rate of premixes will lead to improved consistency of PM components with regards to weight consistency.[10] Of more significant importance was the improvement in green strength with the EZ material. Green cracks are a significant issue for the PM industry and more so with stainless steel due to the low compressibility and green density achieved after compaction.[11] An improvement in green strength will decrease the likelihood of introducing green cracks during part handling or ejection from the compaction press.

The evaluations of machinability in this study demonstrate that both of 304L-EZ and 316L-EZ stainless grades provided much better machinability compared to their standard grade counterpart. The tool life can be extended even at fast cutting speeds, indicating that the easy-machinable stainless steel powder can offer better productivity and longer tool life compared to their standard grades.

On the other hand, the results obtained in this study indicated that the 316L materials were easier to machine than the 304L materials. This finding obtained from turning tests was correlated to those obtained from drilling tests reported for either wrought or sintered 300 series steels in the literature.[15] Generally in machining, tool wear may be classified as 1) adhesive wear; 2) abrasive wear, 3) diffusion wear, and 4) fatigue wear, etc.[12] The 300 series stainless steels have soft and gummy matrix so that adhesive wear is considered to be the major cause of tool failure. The 316L material has similar alloying compositions to the 304L material except the 316L material contains additional 2%Mo. The extra alloy content results in a harder material matrix which reduces the adhesive wear making the 316L material more machinable than the 304L material.

CONCLUSION

The newly developed 300 series easy-machinable stainless powders (SS-EZ) have been evaluated for material properties, corrosion resistance and machinability performance. Compared to their standard grade counterparts, the following conclusions can be made from this study:

1. The newly developed SS-EZ powder provides identical compacting and sintered properties. In addition, the use of a special lubricant system designated for this new powder, the SS-EZ was shown to provide enhanced green strength of more than 25%

2. The corrosion resistance of sintered parts made from the newly developed SS-EZ powders was determined to be the same as that of the standard material

3. The newly developed SS-EZ materials offer far superior machinability compared to those of their standard grade counterparts, both in terms of increased productivity and extended tool life

4. The 316L material was found to be relatively easier to machine compared to 304L material, both in the standard and EZ versions.

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