# Machinability Enhancement of PM Stainless Steels Using Easy-Machinable Stainless Steel Powder

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**ABSTRACT**

PM stainless steels present very different machinability behaviors from plain carbon and low alloy PM steels. Since they contain high alloy content without carbon addition, stainless steels become gummy and work harden during machining so that they are difficult to machine. To improve the machinability, conventional machinability enhancers such as MnS and MoS2, etc. may be applied into the materials but the sulfur containing additives can severely decrease corrosion resistance. Resin-impregnation is also a common solution for improving the machinability of stainless steel materials without detrimental effect on corrosion resistance. However, resin impregnation not only greatly increases operation cost but also lacks consistency in improving machining due to density gradients in the components.

In order to provide an effective solution in a cost-effective way, an easy-machinable version of stainless steel powder has been developed based on a modified powder manufacturing technology. Previous study has demonstrated that components made with the newly developed 300 series easy machinable stainless steel powder provide superior machinability in comparison with their standard grade counterparts. In this paper results obtained from evaluations of 400 series stainless steels will be presented. Machinability, material properties, and corrosion resistance of materials made with the newly developed 400 series easy machinable stainless steel powder will be compared with those of their standard grade counterparts.



Presented at PowderMet 2013 in Chicago, USA on June 25, 2013

## INTRODUCTION

Powder metallurgy (PM) can provide significant benefits in minimizing material and energy waste based on its features as a near-net shape technology compared to other manufacturing technologies.[1] Even though secondary operations such as machining can be eliminated or reduced with PM components, machining operations are often required in order to achieve desired dimensional tolerances and surface finish. Depending on the material system and processing routes, the PM materials can present very different machinability due to the differentiations in microstructure and hardness. [2]

Generally PM materials can be classified into three groups: iron-carbon steels (with and without copper and/or nickel additions), low-alloy steels and stainless steels for producing structural components. [3] Stainless steels contain high percentages of chromium and other alloying elements to provide excellent corrosion resistance compared to the other two groups: iron-carbon and low-alloy steels. Since carbon is generally a prohibited element in stainless steel, stainless steels are relatively soft materials and the machinability behaviors are very different from the iron-carbon and low-alloy steels. They are usually difficult to machine as they become gummy and work harden during machining.

In order to improve the machinability of stainless steels, a conventional machinability additive such as manganese sulfide (MnS) has been used in the materials. However, this approach, either admixed or pre-alloyed, results in a severe decrease in the corrosion resistance of stainless steels. [4~6] Another possible approach for improving the machinability of stainless steel is to impregnate resin in the sintered component. The applied resin can 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 when impregnation varies due to density gradients in the components. Therefore, the machinability 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.

Research efforts have been made in developing an easy-machinable version of stainless steel powder grades, called Stainless Steel EZ™ grade, using powder processing know-how and proprietary processes. This easy-machinable version of stainless steel powder has identical alloying contents to its standard grade achieving the same sintered properties and corrosion resistance. In previous studies, materials made with the easy-machinable version of 304L and 316L stainless steel powder demonstrated superior machinability to those made with their standard grades, both in terms of increased productivity and extended tool life.[7] The corrosion resistance of sintered parts made from the easy-machinable version was the same as that of the standard grade counterparts. This paper presents results obtained from evaluations of easy-machinable version of 409L and 430L stainless steel powder based on tests for machinability, mechanical properties, and corrosion resistance compared to their standard grade counterparts.

## EXPERIMENTAL PROCEDURE

### *Materials*

The easy-machinable version of 400 series stainless steel powders, designated here as 409L-EZ and 430L-EZ, were prepared to achieve identical alloying contents to standard 409L and 430L stainless steel powder grades (North American Höganäs High Alloys). These powder grades were produced by water atomization without post annealing and had a nominal particle size of –100 mesh (<150μm). Table 1 lists the typical alloyed elements and amount contained in standard and EZ version of 409L and 430L stainless steel powders. For test sample preparation, 1% lubricant was used in each case to make press-ready premixes.

**Table 1:** Typical Alloyed Elements and Amount Contained in 409L and 430L SS Powder

| Grade | | %Fe | %Cr | %Si | %Nb |
|---|---|---|---|---|---|
| **409L** | Standard | bal. | 10.9 | 0.8 | 0.4 |
| | EZ version | | | | |
| **430L** | Standard | bal. | 16.9 | 0.8 | 0 |
| | EZ version | | | | |

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) for determination of sintered properties and corrosion resistance. For machinability tests, the premixes were compacted into ϕ55 x ϕ35 x 20H mm rings (~186 g) at a green density of 6.5 g/cm$^3$.

The TRS test bars were sintered in a laboratory batch furnace at 1177°C (2150°F) and 1316°C (2400°F) respectively 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***

Sintered TRS specimens were used for measurement of apparent hardness, dimensional change, sintered density and transverse rupture strength in accordance with MPIF Standards.[8] 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, 3 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 B895-05.[9] 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 2. For each specimen, the elapsed time from the beginning of the test until a rating change was determined.

**Table 2:** 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 |
| D | >25% of specimen surface covered with rust or stain |

***Machinability Tests***

Machinability evaluations were performed based on turning and drilling tests. The test parameters are listed in Table 3.

For the turning test, ring specimens were subjected to inner diameter (ID) turning with a NC machine at Farzati Manufacturing Corporation. 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 constant cutting speed. Machinability was evaluated by measuring the insert edge wear after a certain number of machining cuts or passes 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.

For the drilling test, ring specimens were subjected to flat surface drilling with a NC machine at Farzati Manufacturing Corporation. A 3.22mm (1/8 inch) diameter plain high speed steel drill bit made by Chicago-Latrobe was used for the drilling test to drill blind holes with a depth of 10 mm. The machining was conducted in the wet condition with a water based coolant (5%Hocut 795 AS) at a constant cutting speed and feed rate. Machinability was evaluated by counting the number of holes drilled until the drill bit broke or measuring the drill edge wear after a certain number of holes drilled using a Hitachi S-2600N scanning electron microscope.

**Table 3:** Parameters for Machinability Tests

| **Parameter** | **Turning** | **Drilling** |
|---|---|---|
| Cutting speed | 1) 457 m/min (1500 sfm)<br>2) 549 m/min (1800 sfm) | 1000rpm |
| Feed rate | 0.1 mm/rev (0.004 in/rev) | 0.4 mm/rev (0.016 in/rev) |
| Depth of cut | 0.5 mm (0.02 in) | 10 mm (0.39 in) |
| Length of cut | 20 mm (0.8 in) | - |

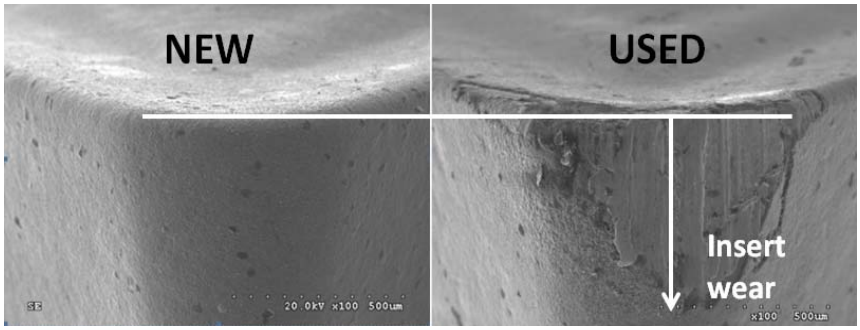



**Figure 1.** Insert wear measurement technique for turning

## RESULTS

### *Sintered Properties*

The sintered properties of easy machinable (EZ™) version of 409L and 430L materials were evaluated to compare to their standard counterparts. Table 4 and 5 show the results after sintered at 1177°C (2150°F) and 1316°C (2400°F) in 100%$H_2$ atmosphere respectively. The high temperature sintering greatly increased the sintered density, mechanical strength and hardness compared to the sintering at lower temperature. The carbon and nitrogen contents of the sintered materials were within acceptable levels, indicating that good sintering was achieved. No noticeable differences were observed in the sintered properties of these materials when sintered under the same conditions. At both of sintering temperatures, the EZ grades achieved very similar sintered strengths, hardness and dimensional change compared to their standard grades.

**Table 4:** Sintered Properties of the Test Premixes at 1177°C (2150°F)

| **Property** | **409L** | **409L-EZ** | **430L** | **430L-EZ** |
|---|---|---|---|---|
| Sintered density, g/cm$^3$ | 6.62 | 6.57 | 6.66 | 6.63 |
| Carbon content, %C<br>Nitrogen content, %N | 0.01<br>0.002 | 0.01<br>0.003 | 0.008<br>0.003 | 0.006<br>0.003 |
| Transverse rupture strength,<br>MPa<br>(x 10$^3$ psi) | 765<br>(111) | 752<br>(109) | 848<br>(123) | 841<br>(122) |
| Hardness, HRB | 38 | 38 | 41 | 42 |
| Dimensional change, % | -2.25 | -2.16 | -2.88 | -2.88 |

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

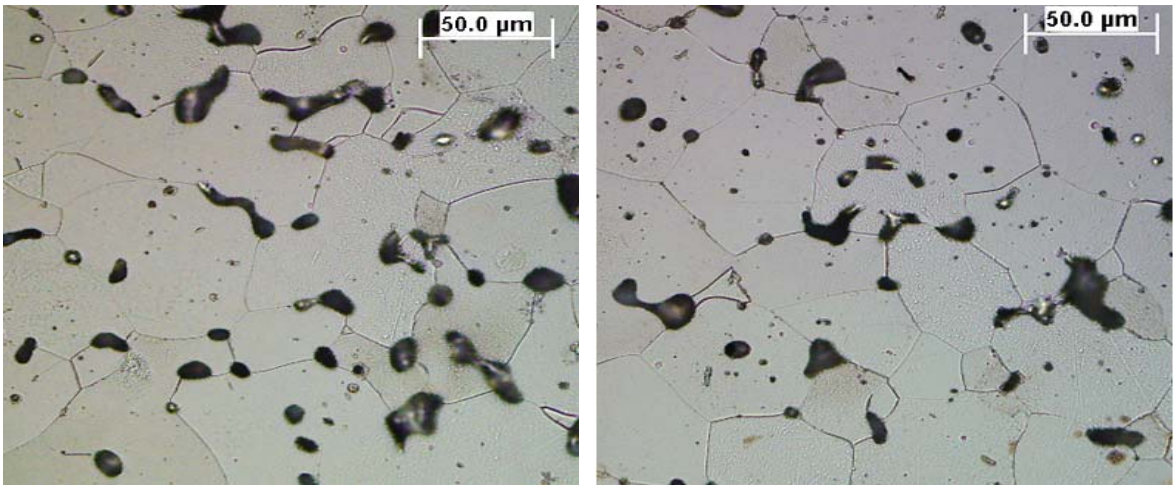
**Table 5:** Sintered Properties of the Test Premixes 1316°C (2400°F)

| **Property** | **409L** | **409L-EZ** | **430L** | **430L-EZ** |
|---|---|---|---|---|
| Sintered density, g/cm$^3$ | 7.28 | 7.28 | 7.22 | 7.25 |
| Carbon content, %C<br>Nitrogen content, %N | 0.002<br>0.001 | 0.002<br>0.001 | 0.006<br>0.003 | 0.003<br>0.002 |
| Transverse rupture strength,<br>MPa<br>(x 10$^3$ psi) | 1055<br>(153) | 1069<br>(155) | 1103<br>(160) | 1089<br>(158) |
| Hardness, HRB | 59 | 61 | 63 | 63 |
| Dimensional change, % | -4.72 | -4.80 | -4.96 | -4.88 |

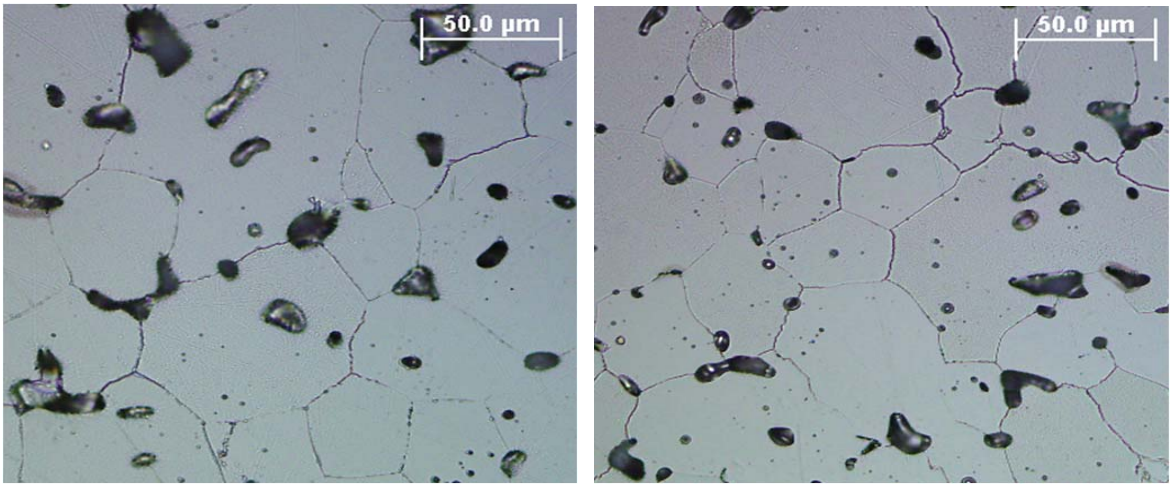
Note: all samples were compacted at 40 tsi and then were sintered at 1316°C (2400°F) for 30min. in 100%v/o $H_2$

***Microstructure***

The sintered ring specimens used for machinability tests were selected for microstructure analysis. The results are shown in Figure 2. All of the tested materials exhibited a well sintered ferritic structure. No differences in microstructure can be observed between the EZ grades and their standard grades. For microhardness (MHV) of matrix, the EZ materials have similar values to their standard grades. However, the matrix of 409L materials is slightly harder than that of 430L materials even though they contain 6% less chromium. This increased microhardness is a result of the additional 0.4%Nb contained in the 409 stainless steels.




**409L** MHV 176 (155-188) **409L-EZ** MHV 172 (159-191)




**430L** MHV 162 (154-168) **430L-EZ** MHV 159 (152-170)

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

***Corrosion Resistance***

The corrosion resistance of 409L standard and EZ™ version stainless steel materials was evaluated by immersion of the materials in 5%NaCl solution. The results are shown in Table 6. For each material, a total of 3 TRS test bars were used. For comparison, the 409L+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 264 hours (11 days) and 504 hours (21 days) respectively.

As expected, the 409L material containing 0.3%MnS started to rust within 24 hours and all of test bars reached "D" rating after 24 hours. Similar results were reported in previous study with 316L material containing 0.3%MnS.[7] For 409L standard material, one test bar developed stains on the surface within 24 and reached "D" rating after 24 hours while the remaining two test bars maintained in "A" rating (no rust or stain) and "B" rating (<1% rust or stain) even after immersion in the salt solution for 504+ hours (21 days). The extensive rust or stains occurred on one of 409L standard material appears to have been caused by powder contamination based on the rust or stain appearance. For the EZ version of 409L material, it exhibited good corrosion resistance. All of three test bars remained in the "A" rating for 504+ hours (21 days) after they immersed in the salt solution. The corrosion test results demonstrate the EZ version of stainless steel material performs in the same manner in corrosion resistance as its standard material.

**Table 6:** Results of the Corrosion Tests

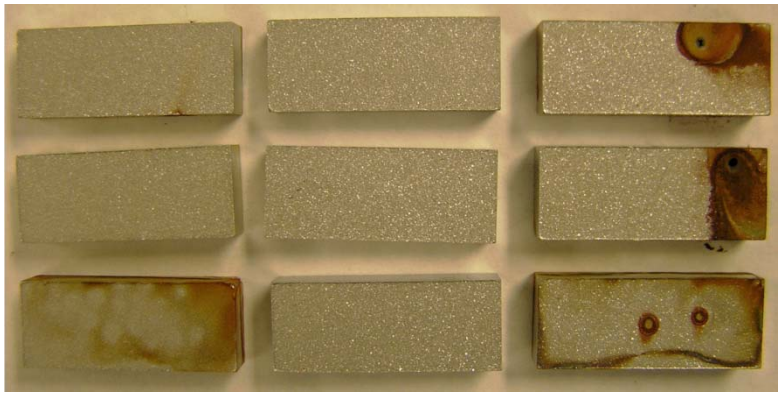
| Material | 409L | | 409L-EZ | | 409L +0.3%MnS | |
|---|---|---|---|---|---|---|
| Corrosion Resistance | hours | # of bars | hours | # of bars | hours | # of bars |
| "A" rating | 504+ | (1) | 504+ | (3) | 2 | (1) |
| "B" rating | 504+ | (1) | -- | -- | 8 | (1) |
| "C" rating | -- | -- | -- | -- | 8 | (1) |
| "D" rating | 24 | (1) | -- | -- | 24 | (3) |

Note: total 3 test bars were tested for each material, sintered for 30 minutes at 1316 °C (2400°F) in 100% $H_2$



**409L** **409L-EZ** **409L+0.3%MnS**

**Figure 3.** Corrosion status of specimens immersed in 5 wt%NaCl solution for 264 hours



**409L** **409L-EZ** **409L+0.3%MnS**

**Figure 4.** Corrosion status of specimens after immersed in 5%wt NaCl solution for 504 hours (21 days)

***Machinability Evaluation-Turning***

Inner diameter (ID) turning was employed to determine relative machinability of the 400 series stainless steel 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 409L and 409L-EZ ring specimens at two different cutting speeds. At a cutting speed of 549m/min (1800sfm), the normal 409L material could only be cut for 30 passes before the tool wear exceeded the benchmark of 200 μm. Excessive wear occurred after cutting the normal 409L material for 60 passes. In contrast, the 409L-EZ material could be cut for 120 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 409L, the tool life was extended to 120 passes but it failed after cut 150 passes. Under the same conditions, the 409L-EZ material machined more easily than its standard counterpart. Small initial tool wear was observed after cutting the 304L-EZ for 150 passes. For comparison, the wear status of inserts after machining the standard and EZ version of 409L materials at different cutting speeds is shown in Figure 6.

For 430L and 430L-EZ materials, similar differences in machinability were observed as seen with the 409L materials. As shown in Figure 7, the normal 430L material caused the tool failure after it was cut for 50 passes at a cutting speed of 549m/min (1800sfm), and 150 passes at a cutting speed of 457m/min (1500sfm) respectively. In contrast, the 430L-EZ material could be cut for 100 passes and 150 passes respectively under the same conditions without tool failures. The wear status of inserts after cutting the standard and EZ version of 430L materials at different cutting speeds is shown in Figure 8.

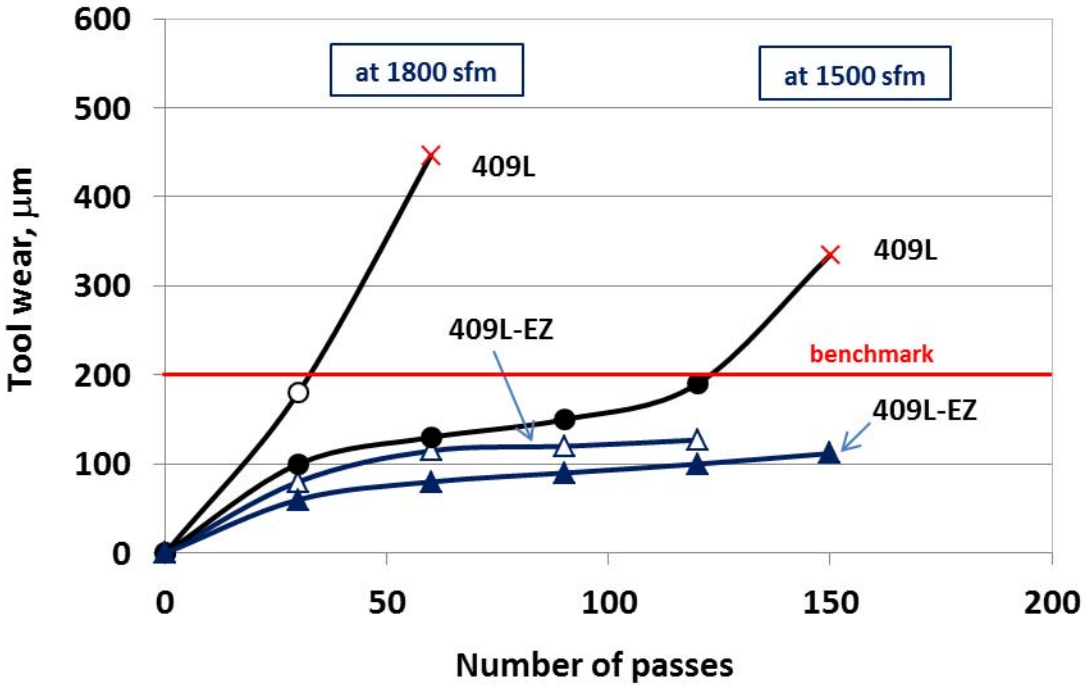



**Figure 5.** Comparisons of tool wear in turning –409L and 409-EZ materials

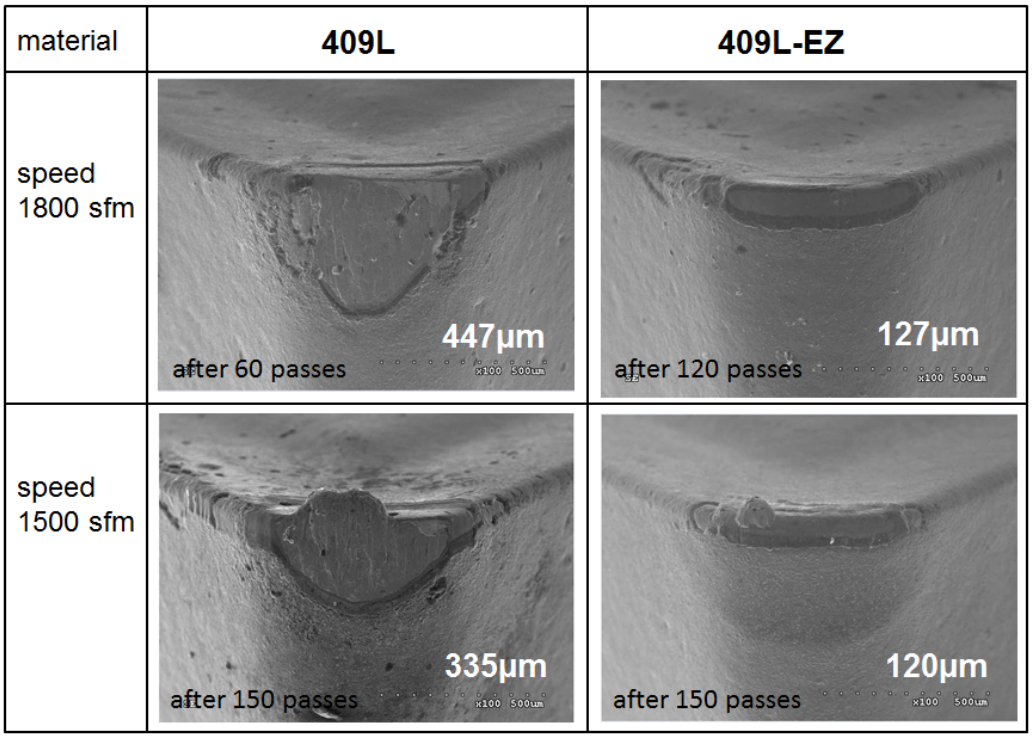



**Figure 6.** SEM photographs of insert wear status in turning – 409L and 409-EZ materials

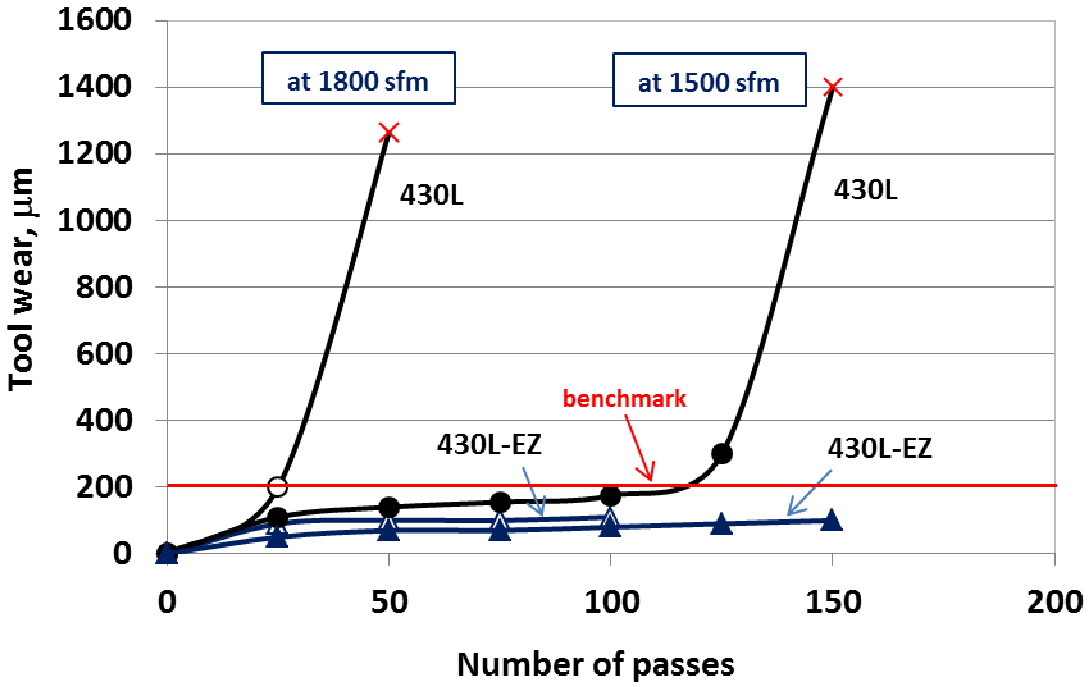



**Figure 7.** Comparisons of tool wear in turning –430L and 430-EZ materials

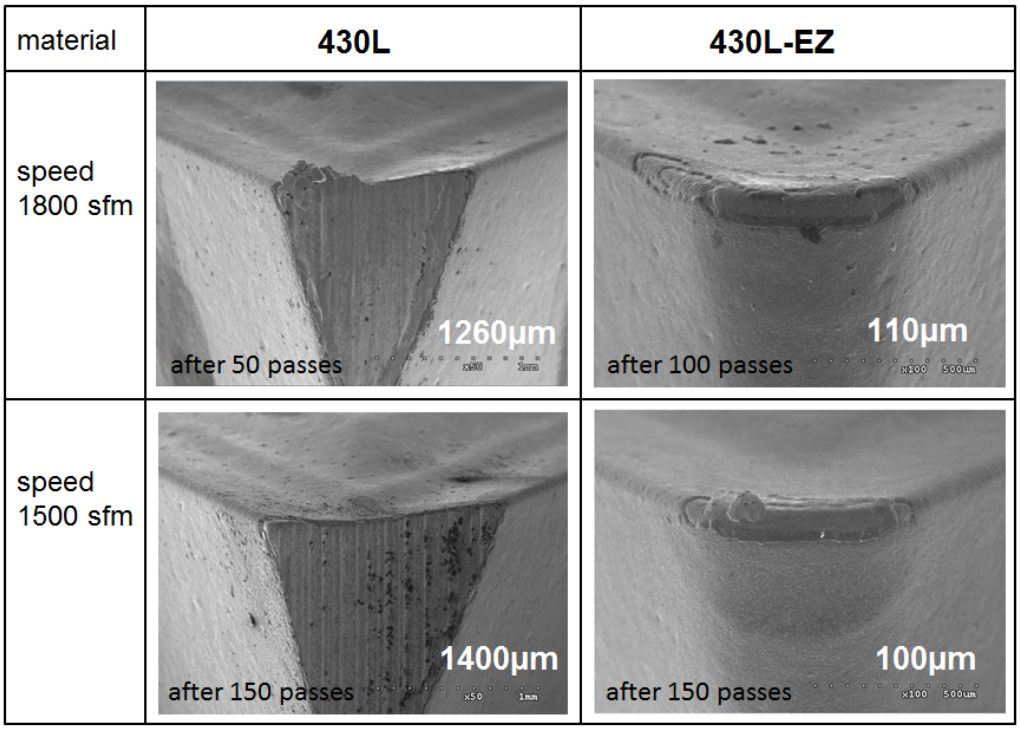



**Figure 8.** SEM photographs of insert wear status in turning – 430L and 430-EZ materials

***Machinability Evaluation-Drilling***

Drilling on the flat surfaces of the ring specimen was also used to determine relative machinability of 400 series stainless steel materials. The machining was performed in the wet condition with a water based coolant at a cutting speed of 1000 rpm to drill 10mm depth of blind holes. In order to create tool wear using limited test rings, the tests employed a feed rate of 400mm/rev that was much higher than the speed recommended for stainless steels. For each material, the drilling test was repeated at least three times under the same conditions and a new drill bit was used for each test. The relative machinability was determined based on the average number of holes drilled.

Figure 9 presents the relative machinability of the tested 400 series stainless steel materials in drilling operation. Compared to their standard counterpart materials, both of EZ version materials, 409L-EZ and 430L-EZ, exhibited better drilling performance but the 409L-EZ material provided greater improvement than the 430L-EZ material. The percentage of improvement in machinability is >148% with the 409L-EZ material and 54% with the 430L-EZ material respectively under the tested conditions. Figure 10 displays the tool wear status of drill bits that were terminated before they were broken. Excessive wear developed on the drill edges when the 409L and 430L standard materials were drilled for less than 20 holes while less wear was observed after the drill bit drilled for 72 holes in the 409L-EZ and 430L-EZ materials.

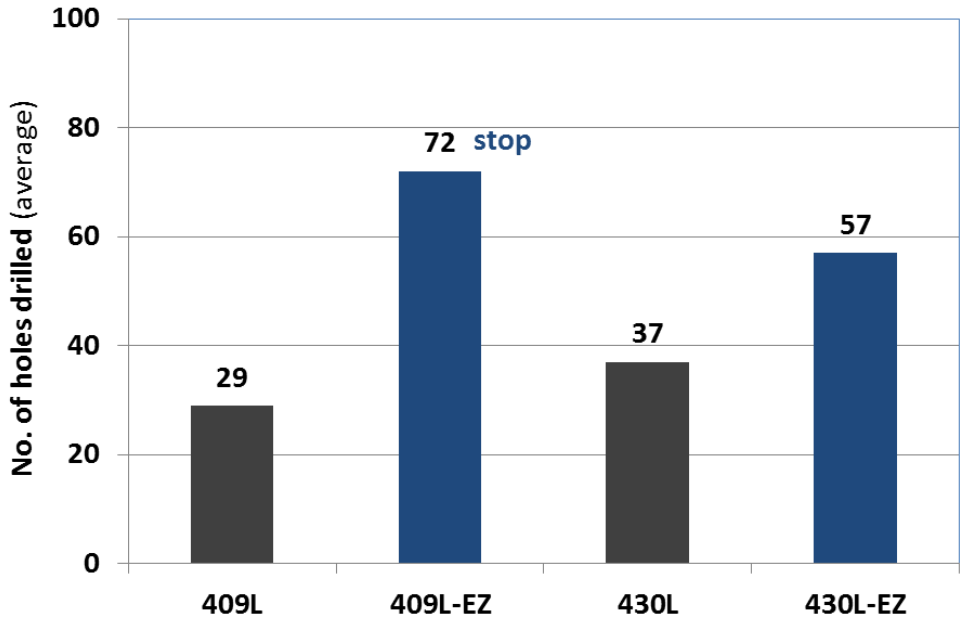



**Figure 9**. Relative machinability in drilling – 409L, 409L-EZ, 430L and 430L-EZ materials

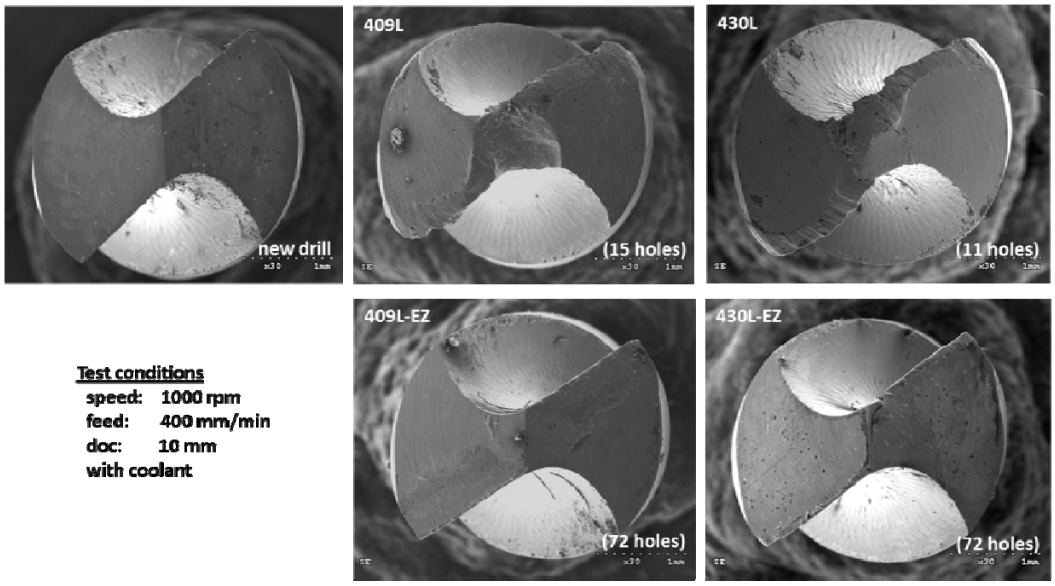



**Figure 10**. SEM photographs of tool wear status in drilling – 409L, 409L-EZ, 430L and 430L-EZ materials

## DISCUSSION

The stainless steel EZ™ grades were manufactured based on proprietary powder processing technologies aiming to achieve the same material characteristics as their standard grades while providing an easy machinability solution. The results obtained in this study have demonstrated that the EZ grades have identical sintered properties to their standard grade counterparts under either low or high sintering temperatures. Although it contains 6% more additional chromium, the 430L materials can only provide slightly higher sintered strength and apparent hardness than the 409L materials. Unlike the material added with MnS as machinability aid that decreased severely in corrosion resistance, test with 409L materials has demonstrated that the EZ grade has the same level of corrosion resistance as its standard grade.

Regardless of the type of machining operation (drilling or turning) applied, the evaluations of machinability in this study demonstrate that both of 409L-EZ and 430L-EZ stainless steel powders provided much better machinability than their standard grade counterpart. The tool life can be extended even at fast cutting speeds, indicating that the EZ version of stainless steel powder can offer better productivity and longer tool life compared to their standard grades. In previous study on 304L and 316L stainless steels, the materials made with the EZ powder grades were more machinable than the materials made with the standard powder grades.[7] These findings are summarized in Figure 11.

As shown in Figure 11, all of the EZ versions, whether it is ferritic stainless steel (400 series) or it is austenitic stainless steel (300 series), provide better machinability than their standard grades. This study showed that the ferritic stainless steel materials were more difficult to machine than the austenitic stainless steel materials.

Generally in machining, tool wear may be classified as 1) adhesive wear; 2) abrasive wear, 3) diffusion wear, and 4) fatigue wear, etc.[10] The stainless steels have soft and gummy matrix so that adhesive wear is considered to be the major cause of tool failure. Although the 300 series materials contain much more alloyed elements and contents than the 400 series materials, there is no significant difference in the

microhardness (MHV) of matrix between the two groups of materials. The MHV was measured approximately ranged from 150~200 based on the tests in the studies. Therefore, making the 300 series materials more machinable than the 400 series materials are considered as the contribution of the extra alloy content: 1) the resulted austenitic structure is less adhesive than the ferritic structure, or 2) a harder material matrix is easier to be created during machining and thus reduces the adhesiveness. Stainless steel materials are prone to work hardening due to the high alloying contents and low thermal conductivity. The work hardened layer is typically less than 0.1mm (0.004in) so that it is recommended to set the depth of cutting larger enough to cut below the layer left by the previous cut.[11] In this study, the depth of cutting was 0.5mm (0.02in) so that the effect of work hardening on machinability is considered as minimal.

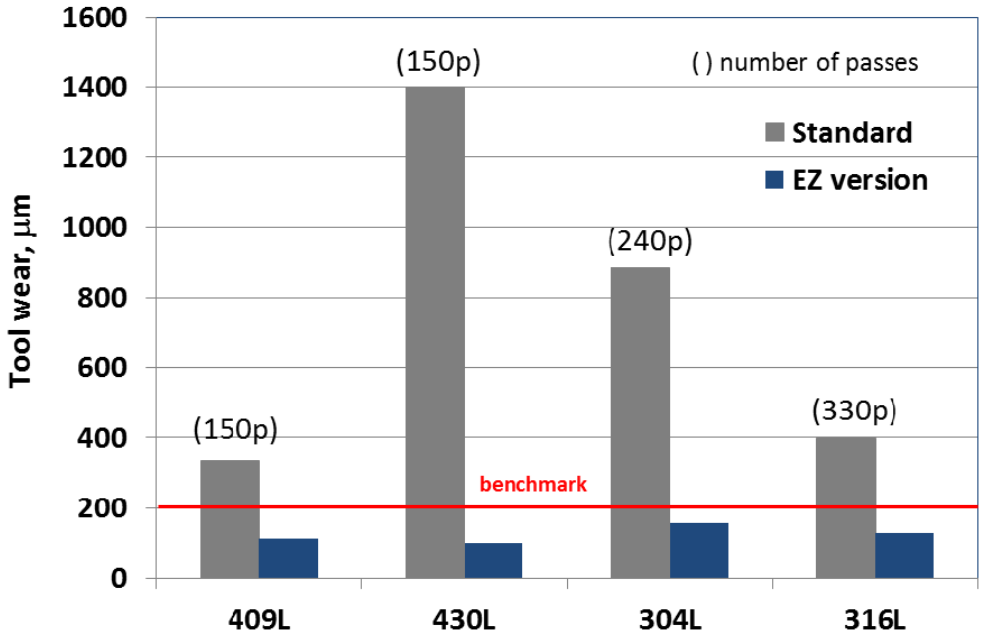



**Figure 11.** Machinability comparison between the stainless steels made with standard and EZ grades (Tool wear in turning after cutting at 1500 sfm for different passes)

## CONCLUSION

The easy-machinable version of 400 series stainless steel powders 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 EZ version of 400 series stainless steel powder provides identical sintered properties to its standard grade

2. The corrosion resistance of sintered components made from the EZ version of 400 series stainless steel powder is the same as that of its standard material

3. The easy machinable 400 series stainless steel powder offers superior machinability compared to those of their standard grade counterparts, both in terms of increased productivity and extended tool life. In this study, the tool life has been extended at least 100% for fast turning and 50~150% for fast drilling

## ACKNOWLEDGEMENTS

The authors would like to thank Paul Hofecker for the specimen preparation, Joshua Valko for the material testing, and Sarah Ropar for metallography and machinability testing.

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