On the Machinability of AISI304L and S-bearing 304L-type Sintered Stainless Steels*

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Synopsis

Machinability of 304L sintered steel is quantitatively assessed by means of drilling and turning tests. Generally, the sintered steels have more or less residual pores in the matrix, different from wrought alloys which are regarded as of almost full density, and the cutting resistance for the former is evidently influenced by the density.

It is found that the cutting resistance has the minimum value in the density of approximately 7 g/cm³ in drilling test of AISI304L sintered steel prepared under various pressing and sintering conditions.

In machining sintered steels, shape and density of chips usually varies with density of the given matrix.

It is confirmed in this study that the cutting resistance increases in proportion to $\Delta D = |D_s - D_c|$, where D_s , D_c are the density of a sintered steel and that of cutting chips, respectively.

For S-bearing 304L type sintered steels, cutting resistance decreases monotonically with increasing the amount of S-addition up to 0.4 %, and also tool life is markedly improved compared to that S-free sintered steel, although tool life of sintered steel is unexpectedly shorter than that of wrought alloy.

As a structural feature of S-added sintered steels, it is confirmed by means of X-ray diffraction analysis that there are sulfides present in the form of CrS in the matrix probably because Mn-content in steel is intentionally lowered from the viewpoint of powder metallurgical process.

I. Introduction

In the powder metallurgy, PM parts of the same shape have originally been produced in a mass quantity by a thorough process of powder compacting followed by sintering with the aim of eliminating the machining operation of parts. However, there has lately been a variety of parts-designs which cannot be incorporated with conventional powder compacting, such as parts including radial holes, undercuts and so on.

Such complicated shapes of sintered parts must be attained by secondary machining operation in the finishing stage of manufacturing. Therefore, it is of

major concern to combine secondary machining operation properly with the PM process for parts designing. For this purpose, a study on machinability of sintered materials and also technical concept for machining is needed for practical applications.

Nevertheless, there have been few reports¹⁻⁵⁾ concerning machinability of sintered steels and especially, little systematic^{3,4)} work to evaluate that of sintered stainless steels. Intrinsically, machining stainless steels has been thought to be difficult. Accordingly, a need exists for improving machinability of sintered stainless steels for their wider applications.

The objective of this work is to elucidate the quantitative relationships of the pressing-sintering conditions to machinability and mechanical properties of AISI304L sintered steels, and also the S-additive effect on their machinability.

II. Material and Experimental Procedure

The 19Cr-10.5Ni steel powders equivalent to AISI 304L as a base composition, and S-bearing 304L type powders were produced by means of water atomization⁶⁾ of melts. The latter were made by adding S to the melt prior to atomization. In this case, C, Si and Mn contents alloyed in powders were adjusted to a range⁷⁾ suitable for stainless steel powders for compacting.

The powders were used in this study after being sieved to 100 mesh under. Chemical compositions of sample powders are listed in Table 1, together with apparent density and particle size distribution. The former was measured according to JIS Z8801.

As for pressing characteristics, the green density of compact to which each powder was pressed at 5 t/cm² in dies according to JSPM standard 1-64 was mea-

Table 1.
Characteristics of tested stainless steel powders.

No.	Chemical composition (%)						Apparent density (g/cm ³)	* Size distribution (%)	** Green density (g/cm ³)	*** Sintered density (g/cm ³)	*** Linear shrinkage (%)
	C	Si	Mn	S	Ni	Cr					
1	0.018	0.90	0.21	0.012	10.49	18.78	2.55		6.29	6.50	1.0
2	0.027	0.86	0.25	0.151	10.56	18.95	2.77		6.18	6.43	1.6
3	0.029	0.79	0.22	0.158	10.57	19.11	2.90		6.19	6.46	1.7
4	0.016	0.85	0.09	0.218	10.54	18.83	2.75		6.13	6.52	2.2
5	0.018	0.89	0.07	0.396	10.56	18.85	3.12		6.13	6.54	2.4

No. 1: SUS304L

* Sieve analysis: 100/150, 150/200, 200/250, 250/350, —350 mesh fraction to lower, respectively (in histogram)

** Compacting pressure: 5 t/cm²

*** Sintering: 1 200 °C×1 h in vacuo

Linear shrinkage: Direction of diameter

* Originally published in *Tetsu-to-Hagane*, **66** (1980), 1142, in Japanese. English version received December 3, 1980.

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sured.

Incidentally, 1 % zinc-stearate was premixed with powder as a die-wall lubricant.

Each powder compact was sintered at 1 200 °C for 1 h in vacuo of 10^{-3} Torr after dewaxing (removal of lubricant) at 500 °C, and then sintered density and linear shrinkage were measured. The results obtained are shown in Table 1, together with green density of compacts. Each powder was pressed at a range from 2 to 8 t/cm² into a compact, according to JSPM standard 2-65 for tensile test and into a compact of ϕ 33×35 for machining test. These compacts were sintered in the same conditions as stated earlier. Some of machining test pieces were densified to sintered density above 7.2 g/cm³ by additional operation of coining or forging in dies, and these specimens were provided for tests after re-sintering at 1 200 °C for 1 h in vacuo in order to reduce the influence of work-induced strain, together with wrought materials.

As for machinability, cutting resistance and tool life were quantitatively examined by drilling tests and partially by turning tests under the cutting conditions shown in Table 2. Incidentally, tool life in drilling tests was determined by measuring the total depth of holes to the break-down of cutting edge used for cutting the specimens. An observation was made about color and shape of chips which were obtained during these machining tests and also the density of chips was measured using an air comparison-type hydrometer of Beckmann make. The drill holes were optically observed, and also microhardness of the surface layer was measured with some machined specimens. For S-bearing sintered steel, sulfide morphology was optically observed.

Further, sulfides in the matrix were extracted according to potentiostatic electrolysis method⁸⁾ and then identified in X-ray diffraction profile.

III. Results and Discussion

1. Machinability of AISI304L Sintered Steel

In the powder metallurgical process, the processing conditions, such as compacting pressure, sintering temperature and so on give reported influence on the mechanical properties of sintered steels.⁹⁾ Considering their influences on the machinability, a test was made to check if the above-mentioned influence exists with SUS304L base powder (No. 1).

Figure 1 shows the relation between compacting pressure and the cutting-torque and -thrust in drilling tests of some specimens which were sintered at 1 200 °C in vacuo after compacted at a range from 2 to 6 t/cm², and also shows their measured densities. Evidently, the sintered density tends to increase, and, conversely, the cutting resistance tends to decrease gradually with increase of compacting pressure.

Figure 2 shows the relation between sintering temperature and cutting-torque and -thrust in the drilling tests of some specimens which were sintered at a range from 1 100 to 1 300 °C in vacuo after compacted at 4 t/cm².

Table 2. Cutting conditions of drilling and turning for measurement of cutting force and tool life.

	Drilling		Turning
	Cutting force	Tool life	Cutting force
Tool	SKH9, ϕ 10 Point angle 118 deg	SKH9, ϕ 5 Point angle 118 deg	P20 (0, 6, 6, 6, 8, 0, 0)
Feed rate (mm/rev)	0.10	0.07	0.20
Depth of hole (mm)	13	15	—
Depth of cut (mm)	—	—	2.0
Max. cutting speed (m/min)	10	7~30	—
Cutting speed (m/min)	—	—	100

Fig. 1. Influence of compacting pressure on sintered density and the cutting resistance during drilling in SUS 304L compacts sintered at 1 200 °C for 1 h in vacuo.

Fig. 2. Influence of sintering temperature on sintered density and cutting resistance during drilling in SUS 304L compacts sintered at 1 100~1 300 °C for 1 h in vacuo.

The similar tendency is confirmed as seen in Fig. 1 where sintered density increases, and the cutting resistance decrease with sintering-temperature.

From these results, the alternative relation between the density and the machinability of specimens was predicted and, therefore, evaluated based on the further experimental data in details.

Figure 3 shows the effect of density on the cutting-torque and -thrust and mechanical properties of specimens with wider range of density, some of which were prepared through the densification process of so-called sinter-forging. Both tensile strength and the elongation of specimens simply improve¹⁰⁾ with increasing of density as expected. On the other hand, the cutting resistance tends to decrease with increase of higher density than it. If the cutting resistance curve is extrapolated on high density side in Fig. 3, it would be close to that of wrought steel.

After this test on machinability, further investigation was carried out about the shape and the density of chips obtained, machined surface of drilled holes, and microstructure of specimens. Photograph 1 shows chips and machined surface of drilled holes. A big crack at top part of drilled hole of specimen with 5.55 g/cm³ density indicates certainly that the cutting edge digs out chips during machining. In this condition, it is observed that chips are so-called tear-type in shape and thicker, and get temper-colored indicating of higher machining temperature. Such noticeable features disappear and, concurrently, chip length becomes gradually longer with the increase in sintered density.

Consequently, the tearing at the surface of drilled hole tends to be suppressed, and the machined surface in the sinter-forged specimen of 7.60 g/cm³ density is found to be essentially similar to that of wrought materials.

Photograph 2 shows optical microstructures at vertical section of the surface layer along drilled hole for specimens with density of 5.55 and 6.90 g/cm³, respectively. Their surface layers seem to have undergone appreciable deformation due to plastic flow through

Fig. 3. Influence of sintered density on tensile properties and cutting force during drilling in SUS304L compacts sintered at 1 100~1 300 °C for 1 h in vacuo.

Photo. 2. Microstructures at vertical section of drilled hole in SUS304L compacts sintered to various densities.

	P/M	P/M Forging	Bulk
Cutting Chips			
Drilled Hole			
Ds	5.55 g/cm³	6.90	7.60

D_s: Sintered density
Photo. 1.
Cutting chips and surface of drilled hole in SUS304L compacts sintered to various densities.

machining operation, and also the internal pores in the layer consequently have changed in shape. The plastic flow layer is found to get deeper with a decrease of sintered density and eventually have some cracks, indicating that the surface layer is possibly influenced by strong cold working during machining.

Figure 4 shows the distribution of micro-vickers hardness at the surface layer of drilled hole. Hardened layer of specimens is deeper for the lower density specimen corresponding well to that of plastic flow layer shown in Photo. 2. The same phenomena was observed at the top part of drilled hole.

Figure 5 shows the relationship of the density of specimen before machined to that of chips sheared off in drilling test. The density of chips shows a fixed value of approximately 7.3 g/cm³ for specimen with density less than 7 g/cm³ and a little less than its value in both cases of specimens with density above 7 g/cm³ and wrought steel.

If the difference between the density of specimens and chips obtained is expressed as follows:

$$\Delta D = D_c - D_s$$

Fig. 4. Distribution of micro-vickers hardness on the surface layer of drilled hole for SUS304L compacts sintered to various densities.

Fig. 5. Influence of sintered density on cutting chip's density and $|\Delta D|$ in drilling for SUS304L compacts sintered at 1 200 °C for 1 h in vacuo.

where D_s and D_c are the density of specimens and chips, respectively, ΔD is plus for less than about 7 g/cm³ in density, while ΔD is minus for more than 7 g/cm³. When chip shape is compared as in Photo. 1, it is discontinuous-type (tear-type) at lower density, and then it changes into continuous-type at 6.9 g/cm³ and above. In the case that this chip shape is related to ΔD value, ΔD is plus for discontinuous-type and is minus for continuous-type. Accordingly, it is understood that ΔD is usually inclined to change with chip shape in drilling test.

Figure 6 shows the relation between $|\Delta D|$, absolute value of ΔD , and cutting torque in drilling test. The cutting torque is a function of $|\Delta D|$, including that of wrought alloy, and is prone to get higher for larger value of $|\Delta D|$. Generally, the energy for machining is consumed in machining and shearing off the surface layer into chips, and further, in the change of their density for conventional sintered materials. As a summary, it is recognized that the cutting resistance increases in proportion to the magnitude of $|\Delta D|$. In order to make further investigation on this phenomena, turning test was carried out under cutting condition shown in Table 2.

Fig. 6. Relationship between cutting torque and ΔD in drilling for SUS304L compacts sintered at 1 200 °C for 1 h in vacuo.

Fig. 7. Influence of sintered density on cutting chip's density and principal force in turning for SUS304L compacts sintered at 1 200 °C for 1 h in vacuo.

Figure 7 shows the relationships between the density of specimen before machined and that of chips cut off in turning test.

The density of chips D_c remains nearly constant independent of the density of specimens as found in the previous drilling test while $|4D|$, and also cutting resistance are inclined to get increased for the lower density specimens. From the results described above the change of density from specimen to chips is considered as a particular phenomena for sintered materials of which residual pores give big influence upon cutting resistance regardless of machining process and conditions.

As described above, the machinability of AISI 304L sintered steel is classified into three ranges; first, lower density for which tensile strength and ductility of specimen are lower and cutting resistance is higher, secondly, medium density for which the cutting resistance increase with favorable improvement of tensile strength and ductility. The machining mechanism for each step mentioned above is considered as follows.

For the lower density specimens where lots of pores are in the matrix, chip shape remains as tear-type. It is reported that such a discontinuous-type chip can usually be formed when ductile cast and wrought steels (of full density) are machined under poor lubricating conditions. The machining problem of non-lubricant case in the present work is apparently considered as that of rather ductile material since sintered material of low density shows very large deformability under compressive force as stated before. That is to say the material is still more densified and at the same time sheared off into chips under the influence of compressive stress applied during machining operation. Extra energy is required for deformation of densified chips and subsequently the cutting resistance increases. As the result of the deformation, a change of microstructure occurs as seen in Photo. 2, and work-hardening is shown in Fig. 4 for machined sintered steel. As chips are gradually discharged out of drilled hole through repetition of pressing and separation, the chip shape is discontinuous-type.

For medium density specimens, the chip shape is of combination of continuous and discontinuous-type and consequently chips get thinner. In this case that there are fewer pores in sintered material, large deformation is usually observed for machined material. It is confirmed from thinly sheared chips as seen Photo. 1 that the pores in the matrix act as stress concentration sites, and the energy necessary for change in density from unmachined material to chips is probably small because of less increase in cutting resistance.

For higher density specimens with few residual pores, chip shape becomes continuous-type as seen in Photo. 1 leading to less stress concentration effect. For that reason, the mechanical properties are evidently improved and the energy consumed for machining is larger and thereby the cutting resistance gets higher in proportion to the density of specimen. The cutting resistance curve can be extrapolated to

that of wrought steel on high density side in Fig. 3 and also the chip shape is also similar to each other.

2. Effect of S-addition on Machinability of AISI304L Sintered Steel

Sulfur is used as one of additives to improve the machinability of conventional cast steel in the form of MnS and also to improve¹¹⁾ effectively tool life in cutting operation especially at low cutting speed. On the other hand, Mn-addition to stainless steel powder in powder metallurgy is deliberately kept low on account of powder characteristics. As the machinability in this case was assumed different from that of cast steel, an investigation was made on the influence of S-addition on the machinability of AISI304L sintered steels.

Incidentally, it is said that the addition of S to molten metal tends to change its physical properties and consequently affects the powder characteristics, and pressing and sintering properties of powder produced by water-atomization of such a melt. In this study, sample powders used were adjusted to nearly the similar characteristics of S-free, 304L-type powder with base composition as listed in Table 1 by means of controlling atomizing conditions.

Figure 8 shows the relationships between S-content and mechanical properties and the cutting-torque and -thrust in drilling of sintered steels. In this test the compacting pressure was properly adjusted so that each specimen has fixed density of 6.5 g/cm³ in order to avoid probable deviation of various properties. The influence of S-addition on the tensile strength can be ignored, while elongation as an indication of ductility decreases in proportion to S-content. From the lowering of the cutting resistance with S-content, S-addition is thought to be very effective to improvement of machinability of sintered steel.

Figure 9 is the result of drilling test carried out about No. 4 and No. 5 specimens with a wide range of sintered density.

Fig. 8. Influence of amount of S-addition on tensile properties and cutting resistance during drilling in SUS 304L-type compacts vacuum-sintered to 6.5 g/cm³ of sintered density.

As the result of S-addition to sintered steel, the cutting resistance decreases on all level of density, compared with that of S-free one especially in the range of lower density.

Photograph 3 shows chips and surface finish of drilled hole for S-bearing sintered steels. It is found that S-addition has the remarkable effect on making chips thinner even in low density, and making tearing on surface layer remarkably smaller compared to the case without S-addition. $|ΔD|$ of S-bearing sintered steel is 0.56 g/cm³ for the density of 6.67 g/cm³ in medium density where the cutting resistance for S-free one is relatively lowered indicative of probable improvement of machinability.

Photograph 4 is microstructure at vertical section of the surface layer of drilled hole after machining. There are some sulfides of 5 to 6 μm in length at grain boundary and within grains of the original powder. It is assumed that in machining operation, a lot of microcracks are initiated from such a sulfide and consequently, chips tend to be sheared off finely.

In order to investigate the observed sulfide morphology, the residues extracted electrolytically from specimen were analyzed by means of X-ray diffraction.

Figure 10 shows the result obtained. Sulfur is mainly identified in the form of CrS, and there is no

Fig. 9. Relationship between sintered density and cutting resistance during drilling in S-bearing 304L-type compacts sintered at 1 200 °C for 1 h in vacuo.

D_s 5.57 g/cm³

Photo. 3. Cutting chips and surface of drilled hole in sintered specimen by No. 5 powder.

diffraction profile of MnS. Besides CrS, Cr₂O₃ and αSiO₂ which were assumed to be formed during quench-atomization were identified in residues. Since CrS acts as a stress raiser upon machining, chips are sheared off finely, resulting in a rise in density. As the result, tearing is hardly generated and the cutting resistance is lowered for S-bearing sintered steel.

Figure 11 shows the effect of S-addition on the tool life obtained from the result of drilling test in relation to the sintered density as a parameter. The tool life for S-free, 304L sintered steel of No. 1 gets improved with increasing density but is slightly inferior to that of wrought steel. On the contrary, the tool life of S-bearing sintered steel is remarkably longer than that of S-free one, and tends to get greatly improved with an increase of S-content in steel.

Figure 12 shows the relation between the cutting speed indicated in Fig. 9 and the cutting torque at 300 mm of drill life.

It is confirmed that cutting speed of S-free sintered steel should be controlled slower than that of wrought steel in order to attain the same tool life under a given condition of the cutting torque. This is essentially due to the fact that, although the cutting resistance is lower because of stress concentration effect originated from pores present in the matrix, is inclined to be easily chipped substantially under interrupted cutting condition and to be overheated on account of thermal conductivity-lowered by pores and furthermore, to undergo abrasive wearing in sintered steel containing

Fig. 10. X-ray diffraction profile of sulfide and oxides extracted from sintered specimen by No. 5 powder.

↑: Sulfide

Photo. 4. Sulfides observed at pseudo-boundary of sintered specimen (by No. 5 powder) where micro-crack was initiated by drilling.

Fig. 11. Relationship between cutting speed and drill life for SUS304L and S-bearing 304L-type compacts sintered at 1200 °C for 1 h in vacuo.

Fig. 12. Relationship between cutting speed and cutting torque at 300 mm of drill life.

more hard inclusions of oxide, as seen in Fig. 10, than those of wrought steel.

Meanwhile, since the cutting resistance is markedly reduced for S-added sintered steel, the tool life certainly tends to be extended.

IV. Conclusions

- (1) The sintered density gives remarkable influ-

ence on the cutting resistance. The resistance decreases first, and then increases with density showing the minimum value around 7 g/cm³ of density.

(2) The shape and the density of cutting chips change with the density of materials. The cutting resistance increases in proportion to $\Delta D = |D_s - D_c|$, where D_s , D_c are the densities of specimens and chips, respectively.

(3) S-addition has no influence on the original powder characteristics. The cutting resistance decreases with increase in S-content, and accordingly, tool life can be remarkably improved.

Acknowledgements

The authors wish to thank Mr. Shozo Abeyama, Deputy Manager, and Mr. Sadayuki Nakamura, Researcher of 5th Section, 1st Department of R & D Division, Daido Steel Company, Ltd., for helpful suggestion and aid to machining test.

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