NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 116 SEPTEMBER 2017

Technical Report

UDC 669 . 14 . 018 . 23

Development of Lead-free Free-cutting Steel and Cutting Technology

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Abstract

Recently, it is expected to improve machinability without the addition of lead from the point of view of environmental issues. Nippon Steel & Sumitomo Metal Corporation has developed two types of lead-free free-cutting steel. One of the developed steels is for carbon steel for machine structural use with good chip breakability and tool life. The other is for low carbon free-cutting steel with excellent finished surface after machining. For both steels, the shape control technology of MnS is used to achieve machinability equal to that of leaded free-cutting steel. This paper introduces the development strategy of the lead-free free-cutting steels based on the understanding of the role of lead inclusions in leaded free-cutting steel.

1. Introduction

Along with the trend to reduce the use of substances with high environmental toxicity, the use of lead has decreased worldwide since the late 1990s. Typical examples of regulations of such trend include the Waste from Electrical and Electronic Equipment Directive (WEEE Directive), the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS Directive) and the End-of Life Vehicles Directive (ELV Directive); they were instituted in Europe and led to restrictions on the use of lead and other specific hazardous substances in many other countries.

Leaded free-cutting steel, which contains lead of 0.35 wt% or less (percentage contents hereinafter are given in weight) naturally falls within the range of restriction under the RoHS Directive. However, some maintain that the addition of lead to steel makes it highly machinable to reduce the machining load, and shows promise as an energy saving measure. At any rate, leaded free-cutting steel is presently exempted from the restriction under the said Directive. Nevertheless, Japanese automobile and parts makers began to restrict the use of lead of their own accord, and the development of a lead-free free-cutting steel that can replace conventional leaded free-cutting steel is anticipated.

Japanese steelmakers have studied the development of such steel according to their own philosophies.[1–10] Their approaches can be classified into the following: (1) effective use of MnS of sulfured free-cutting steel; and (2) use of nonmetallic inclusions and precipitates other than MnS. Nippon Steel & Sumitomo Metal Corporation endeavored to develop such steel through the former approach, and established its own methods for evaluating machinability as a result of the studies. The present paper introduces the company's activities to improve the machinability of steel materials referring to past reports.

2. Approach to Elimination of Lead from Free-cutting Steel

Free-cutting steel is divided into two types according to application. One is free-cutting steel for machine structural use, used mainly for the drive systems and undercarriages of automobiles. While this type of steel is required to have high strength as well as excellent machinability without sacrificing strength, free-cutting elements, namely Pb and S, exist in steel as inclusions, and they act as an initial point of failure depending on their amount and size. For this reason, their addition is limited: at present, the maximum amount of Pb that can be added is 0.2%, and that of S 0.1%, approximately. The other type is low-C free-cutting steel, also known as SUM steel under JIS, used widely for OA devices, hydraulic machines, etc., for which machining accuracy is more important than strength. For the sake of machining accuracy, the addition of Pb or S up to roughly 0.3% is allowed.

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As stated above, different degrees of machinability are required for the two types. Owing to the smaller amounts of the free-cutting elements, the chips of the former have less tendency to break into short pieces, and handling of the chips at users' manufacturing works is sometimes troublesome. As Pb is especially effective at helping chips break into small pieces, its elimination requires measures to improve the chip breakability. The latter, on the other hand, poses little problem of chip handling thanks to the large amount of free-cutting elements and consequent nonmetallic inclusions scattered in quantities in the matrix, but because of the nature of the products for which it is used, machined surfaces with good quality are required. In view of all these, before actually working on the elimination of Pb from free-cutting steel, Nippon Steel & Sumitomo Metal concentrated efforts on clarifying the machinability improvement mechanism of Pb in the two types of free-cutting steel.

First, we considered the free-cutting steel for machine structural use. **Figure 1**[11] shows scenes of orthogonal cutting of specimens prepared from JIS S55C with and without Pb addition taken through a high-speed camera, and the appearances of their chips; here, P20 tools of cemented carbide were used. During the observation through the high-speed camera of steel A without Pb addition, the cutting edge of the tool cut into the work, the chips accumulated on the rake face while the shear angle gradually decreased, and finally the chips broke along the primary shear zone around the cutting edge. All these repeated cyclically; this process is similar to the shear-type cutting mechanism. For steel B with Pb addition, in contrast, the curling radius of the chip was smaller, and there was less change in the chip thickness, the chip being of a desirable flow type. To confirm the change in the chip shape relative to Pb addition, we examined the chip forming mechanism of leaded free-cutting steel by the machining test under a scanning electron microscope (SEM).

Figure 2[11] shows the cutting situation: as the tool advances, the lead inclusion deforms in the shear direction in the primary shear zone, and a crack or a slip plane forms starting from the deformed inclusion. As seen here, lead is considered to accelerate shear slip, and consequently, cracking in shear zones, which suppresses the deformation of the chip matrix. This indicates that the machinability improvement effect of lead is due, not only to the low frictional force at the rake face because of the low melting point of lead, as had been assumed conventionally, but also to the effect of stabilizing the formation of chips due to the high plasticity of lead and consequent small deformation resistance of the chip at the shear zone.

Next, we focused on the surface quality improvement effect of lead in low-C free-cutting steel. **Figure 3**[12] is a photomicrograph of a built-up edge (BUE) that formed near the cutting edge at the orthogonal cutting interruption test of leaded free-cutting steel (JIS SUM24L) taken through an SEM. In the shear zone above the BUE, a crack is seen to stretch from MnS deformed under shear strain by the friction on the rake face advancing towards the BUE. Lead inclusions crystallize around MnS grains in this type of material before machining and such lead inclusions are considered to help cracks form and suppress the growth of BUEs.

In addition, the BUE consists of hard and fine ferrite in which C is condensed. Also when BUEs grow coarse during machining, the quality of the machined surface deteriorates because they fall off the tool and stick to the machined surface. From this, we presumed that the surface quality improvement effect of SUM leaded free-cutting steel is due to the fact that BUEs forming at the cutting edge during machining are prevented from growing by cracks around them start-

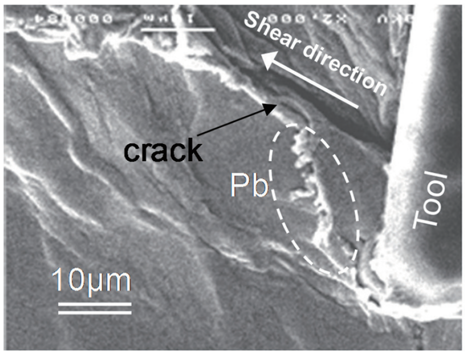

Fig. 2 Crack initiation at the primary shear zone during orthogonal cutting of leaded steel in SEM[11]

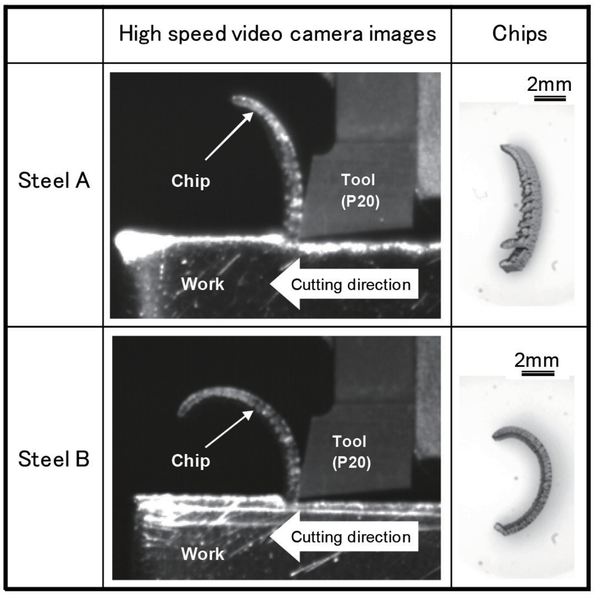

Fig. 1 In-situ observation of orthogonal cutting and chips[11]

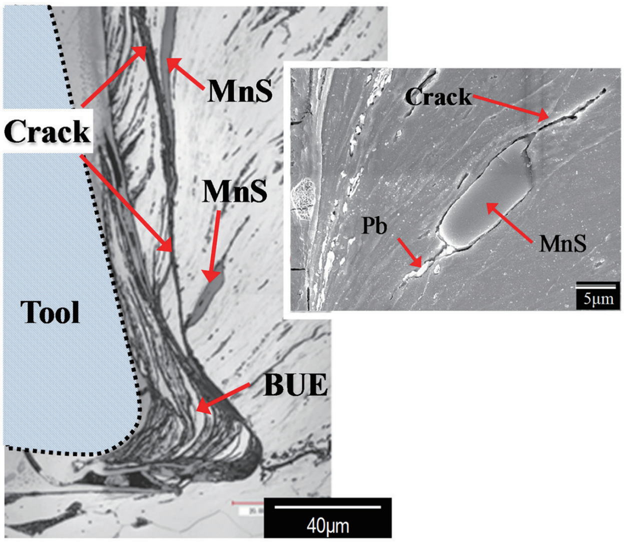

Fig. 3 Microstructure in the vicinity of built-up edge with leaded free-cutting steel, JIS SUM24L[12]

ing from lead and MnS inclusions, and as a result, an ideal condition is maintained at the cutting edge, producing a machined surface with good quality.

The development of lead-free free-cutting steel based on shape control of MnS was advanced following the philosophy above. Principal events of the development are presented in the following Section 3.

3. Development of Lead-free Free-cutting Steel

3.1 Lead-free free-cutting steel for machine structure

As stated in Section 2 above, the main issue regarding the free-cutting steel for machine structural use was improvement of the chip breakability. From the chip forming process clarified through the high-speed camera, the key was how to suppress the deformation resistance in the shear deformation zone. In seeking measures to decrease the resistance to shear deformation originating from nonmetallic inclusions without changing the S content, we focused on the formation of fine MnS particles. SumiGreen™ S[13, 14] is Nippon Steel & Sumitomo Metal's new lead-free free-cutting steel for machine structural use. It demonstrates the same chip breakability as leaded free-cutting steels thanks to having MnS form in fine particles through delicate control of the steelmaking processes. **Figure 4** compares the developed steel with a lead-free steel in this aspect. It is also possible to lower the melting point of oxide non-metallic inclusions by applying the Ca treatment in a converter in addition to the fine particle formation of MnS. Thanks to these measures, decreasing tool wear and improving the shape of chips have been enabled.

The developed steel has earned a high reputation among users, and is being used for crank shafts and other automotive parts.

3.2 Lead-free low-carbon free-cutting steel

Low-carbon free-cutting steel contains free-cutting elements, and as a result, nonmetallic inclusions are dispersed in quantities in the matrix. Chip handling therefore is not a serious problem. Instead, the problem is rather, as clarified through the machining interruption test in the previous section, how to suppress the growth of BUEs and improve the quality of machined surfaces. As solutions to the problem, Nippon Steel & Sumitomo Metal has developed two types of steel.

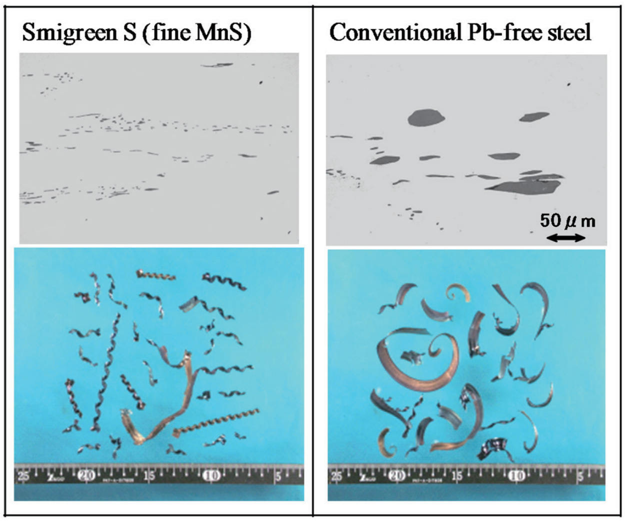

Fig. 4 Comparison of MnS morphology and chips between developed steel (SumiGreen™ S) and conventional Pb-free steel

According to a past report,[15] one of the developed steels contains an increased S amount of more than 0.3%. Through adequate control of the production processes, MnS in this developed steel is made to precipitate in sub-micron particles as shown in **Fig. 5**. These fine MnS particles are captured in BUEs that form during machining, making the BUEs brittle and thus preventing them from growing coarse.

The other type of developed steel contains S in an unprecedentedly high amount of 0.5% or more. Through treatment unique to the company at the steelmaking stage, MnS is made to form particles with small aspect ratios (L/W) evenly dispersed in the matrix. **Figure 6**[16] shows an optical photomicrograph of the MnS particles of the steel and the distribution of the aspect ratios of the particles measured using image analysis. To have such MnS particles dispersed evenly and in quantities, the decreasing rates of O and S contents in molten steel were controlled adequately using slag at the refining stage.[17] We also examined the micro-segregation behaviors of Mn and S during continuous casting, and based on the findings obtained, successfully prevented internal cracks of cast blooms by setting an adequate content range of Mn for the high S content.

Figure 7 shows an example of the results of machinability evaluation of the developed steel, SumiGreen™ CS, through mass production of real parts. The developed steel has realized good surface quality and chip breakability equal to or better than those of conventional low-C leaded free cutting steel under different machining conditions such as turning on an NC lathe for OA parts and grooving on a multi-spindle automatic lathe for automotive parts. In this high-S steel, having spindle-shaped MnS particles with a low aspect ratio, in addition to increasing the S content, proved effective for improving the quality of machined surfaces. We studied this mechanism focusing on the formation of BUEs using steels melted in a laboratory vacuum furnace.

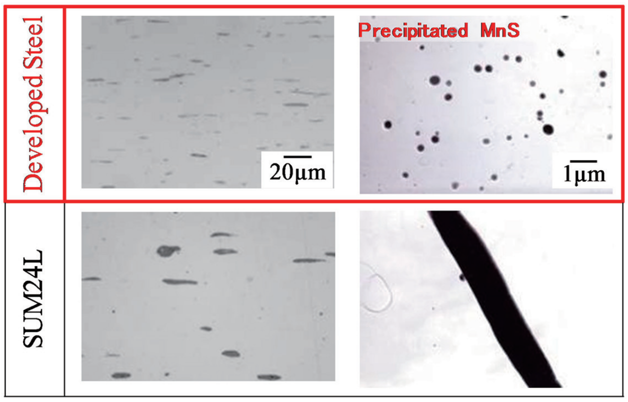

Fig. 5 Comparison of MnS morphology between developed steel and SUM24L steel

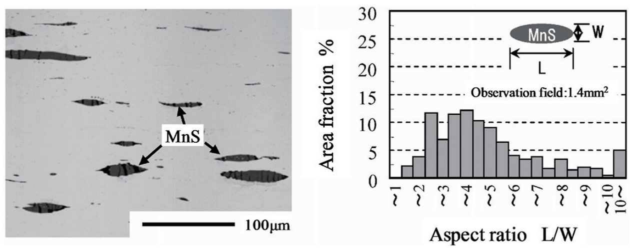

Fig. 6 MnS morphology of developed low-C free cutting steel[16]

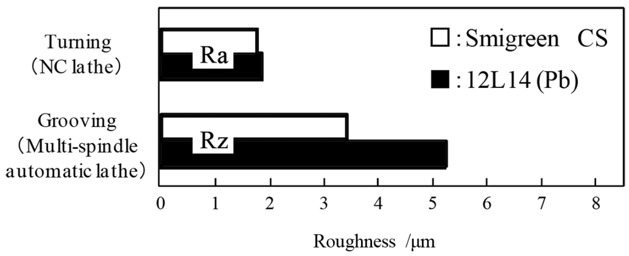

Fig. 7 Machinability in developed steel (SumiGreen™ CS)

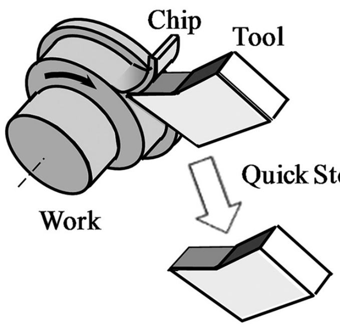

Fig. 8 Schematic illustration of quick stop test in cutting

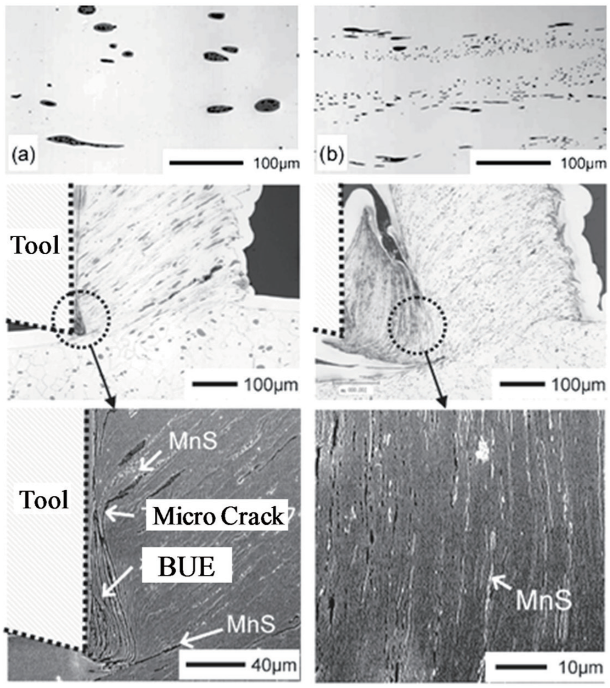

Fig. 9 Effect of MnS morphology on BUE formation [16]

To observe a BUE and the microstructure around it, a quick cutting interruption apparatus was used, whereby the tool is quickly retracted from the position in the course of cutting of a work as shown schematically in **Fig. 8**, so as to immobilize the condition of the work during machining. **Figure 9**[16] shows the distribution of MnS particles obtained by changing the deoxidizing conditions of molten high-S steel and the microstructures near the BUEs forming during cutting at a speed of 50 m/min. Figure 9 (a) shows that with the steel, wherein MnS is in coarse spindle-shaped particles, the BUE is as small as roughly 40 μm. Around the BUE, many micro-cracks are seen to originate from the spindle-shaped MnS particle, as in the case with the leaded free-cutting steel described earlier. Some of the micro-cracks reached the boundary between the BUE and the chip.

In contrast, with the other steel shown in Fig. 9 (b), wherein MnS is in fine or stretched particles, the BUE grew as large as over 200 μm in width. Although micro-cracks were seen near the boundary between the BUE and the chip, they did not separate the two from each other, failing to suppress the BUE growth. The observation above indicates that the manner of micro-crack formation differs depending on the MnS morphology, which affects the growth of BUEs. The high quality of machined surfaces of the developed steel has been achieved thanks to the control of MnS morphology.

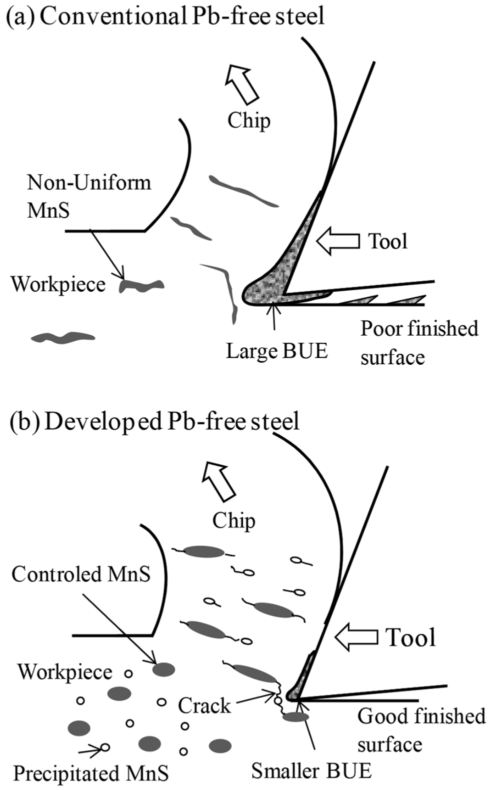

Fig. 10 Schematic illustration showing effect of MnS morphology on BUE formation

Figure 10 schematically shows the effects of the morphology of the MnS particles. This finding led to the development of two types of new free-cutting steels: the first one is marketed under the trade name of EZ, the second one SumiGreen™ CS, and both have earned a high reputation among users. These steels are being used for a wide variety of applications such as automotive parts, OA devices and household appliances. Studies are under way to further expand the field of their application. The development of the two types of steel was awarded the Science and Technology Prize (Development) of the Minister of Education, Culture, Sports, Science and Technology for the fiscal year 2015 (ending in March 2016).

4. Machining of High-hardness Steel

Machining of hardened steel, known in the field as "hard machining," has been attracting attention lately. This section describes Nippon Steel & Sumitomo Metal's activities in relation to this subject.[18, 19]

Many machine components such as gears are required to have high strength as they are subjected to carburizing or other surface hardening treatment. The surface layer turns into a hardened structure, with high carbon contents, having a hardness exceeding 700 HV through carburizing; such material is one of the toughest to machine. Tools of sintered boron nitride (cBN) in cubic crystals are used for cutting the hardened steels[20]. There have been few study reports on the effects of steel chemistry over the wear of cBN tools. In view of this situation, we conducted a turning test using quenched steels containing Si, one of the main alloying elements, in different amounts.

Two specimen steels were prepared from JIS SCr420 by changing the Si content to 0.2 and 1%. Their C contents were 0.8% to simulate a carburized layer. **Figure 11** shows optical photomicrographs of the structures of the 0.2%-Si steel and the 1%-Si steel. Both show typical quenched structure of high-C steel consisting of martensite and a retained γ phase. Their hardness readings were 720 and 725 HV, and the volume fractions of the retained γ phase 22 and 24%, respectively; there was no significant difference between the two in these respects.

Figure 12 shows photomicrographs of the flank wear lands of the tools after machining the two steels for 5 min taken through a scanning electron microscope with energy dispersive X-ray spectroscopy (SEM-EDS). The dotted lines delineate the portion of the tool worn or broken during the machining. The solid lines in Fig. 12 (b) show the boundary between the worn and broken portions. In the case of the 0.2%-Si steel, the wear is homogeneous in the entire flank wear land, which corroborates stable machining. With the 1%-Si steel, in contrast, a large portion of the tool fell off as viewed on the right-hand side, proving that the tool was unable to withstand 5 minutes' work. Both the steels had adhered materials on the worn surfaces of the tools; through EDS analysis, those of the 0.2%-Si steel were found to consist of Fe, and those of the 1%-Si steel of Fe and Si. This seems to indicate that, with high Si content steel, adhesions are promoted owing to affinity with the tool chemistry, and the strength of the tool edge decreases as the wear proceeds, leading to edge breakage, as in the case with the 1%-Si steel.

As stated above, machinability changes markedly depending on the delicate change in steel chemistry even when the metallographic structure and hardness are the same. A major challenge in future research and development, therefore, is to clarify the influences of alloying elements over machinability, and develop new steels of better machinability without sacrificing the performance of the product parts.

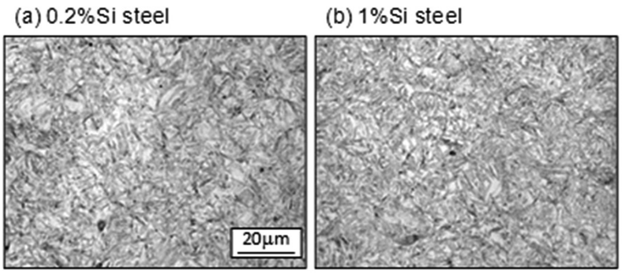

Fig. 11 Microstructure of test pieces

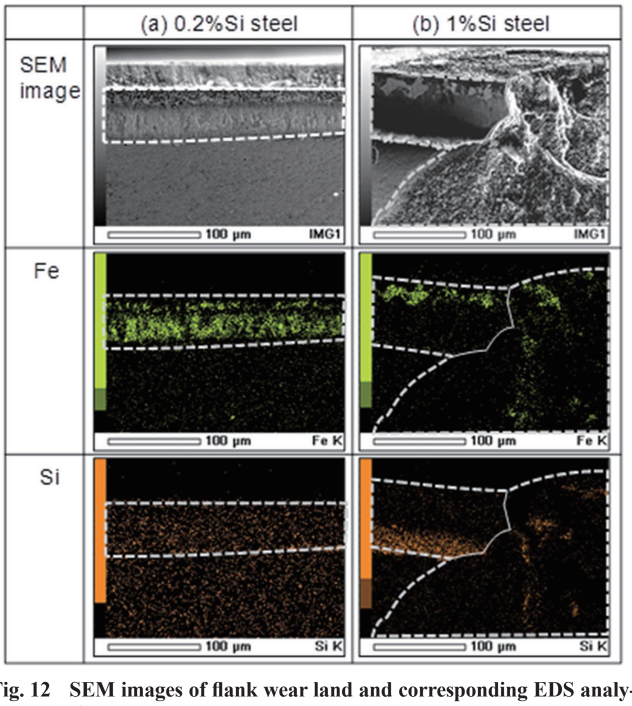

Fig. 12 SEM images of flank wear land and corresponding EDS analysis results

5. Conclusions

The development of lead-free free-cutting steel has been reported herein; the development of such steel aimed to reduce the use of environmentally-hazardous lead. At present, free-cutting steel containing lead is exempt from the restrictions under environmental regulations, but many countries are expected to expand the regulations and the number of restricted substances will increase. In such circumstances, Nippon Steel & Sumitomo Metal has squarely addressed the challenge of developing lead-free free-cutting steel. The fruits of the development, SumiGreen™ S for machine structural use and low-carbon EZ and SumiGreen™ CS, are among the mainstay products of the high-functionality product group, XSTEELIA™, intensively developed and promoted under the banner of SteeLinC™, the trade name of the company's Bar & Wire Rod Unit. Through these development activities, various technologies unique to the company have been established for evaluating the machinability of materials further assisting users through the solution package, SYNERGIA™, for optimizing the conditions of their machining operation in consideration of material properties.

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