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Development of Low-Carbon Lead-Free Free-Cutting Steel Friendly to Environment

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Abstract

Conventionally, low carbon free-cutting steels are added lead (Pb) in order to cut the complicated and precise configurations of various parts such as hydraulic devices for automobiles and the precision parts of OA equipment. In these parts, the first priority in developing lead-free free-cutting steel is not only to facilitate high-efficiency cutting but also to provide, without using lead, an extremely smooth finished surface after machining. This paper introduces the developing strategy and the machinability of the developed low carbon lead free free-cutting steel.

1. Introduction

Growing global environmental concerns in recent years are inclined to force the disuse or to restrict the use of environment-polluting substances. Lead is regarded as one such substance and its use is under some restrictions. Nevertheless, it remains to be an import component in some industrial products. Steel for steel products to be worked by cutting or other machining contains lead added as a component to enhance the machinability of the steel[1)].

For lead in steel, the European environmental regulations (known as EU Directives) for automobiles and electric appliances give special treatment to it as an exception. But the regulations in Japan and Europe are expected to be strengthened[2)]. In fact, an increasing number of large steel consumers including automobile manufacturers and office automation equipment manufacturers voluntarily hold the target of restricting the use of environment-polluting substances and request their suppliers for cooperation to this effect[3)].

Machining is a process of metal working to shape metal material to required form to required precision by cutting off and removing part of the material as chips, under precise control of the destructive phenomenon. Machining can finish the material efficiently and accurately and is therefore frequently used to produce important parts for automobiles, OA equipment components and other products. To steel for such machining applications, lead used to be added to enable the production of high-performance high-efficiency parts and to provide steel consumers with the compatibility of cost efficiency and high product precision (high function). It meant that forcible disuse of lead in steel could not only affect the life of cutting tools but also produce performance and efficiency (cost) problems such as low performance with poor accuracy and the necessity of additional finishing processes. For the purpose of eliminating lead in cutting steel solving at the same time such problems, we successfully developed and commercialized a low-carbon lead-free free-cutting steel as reported in the following sections.

2. Problems of Developing Lead-Free Free-Cutting Steel

The types of steels currently classified as low-carbon free-cutting steels in JIS include resulfurized free-cutting steel (SUM 23) and resulfurized-leaded free-cutting steel (so-called leaded free-cutting steel) (SUM 24L). They contain a large amount of sulfur, and the lead free-cutting steel further contains a large amount of Pb[4)]. **Table 1** shows a typical chemical composition of these low-carbon free-

Table 1 Chemical compositions of typical low carbon free-cutting steel

Grade	C	Mn	P	S	Pb
SUM 23	0.08	1.1	0.083	0.34	–
SUM 24L	0.08	1.1	0.075	0.32	0.28

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cutting steels.

The machinability of steel is generally divided into the three factors of 1) tool life, 2) chip controlability, and 3) accuracy (in size, surface roughness, etc.) of being machined, and lead in steel is effective for enhancing these factors. The tool life and the chip controlability are often managed by the development of tool technology, but the accuracy, particularly the surface roughness, greatly depends on the quality of steel to be machined. High machinability is an essential requirement for high performance of free-cutting steel. If the machinability in terms of surface roughness of a free-cutting steel is low, finished parts of this steel by machining may have poor joint or slide contacts with other mating parts and deteriorate the functions of the assembly.

The contact area of a cutting tool tip and a steel part being machined is hot, high-stressed, and cohesive to each other. Under such an environment, lead in the steel is known to be effective for brittleness of the steel and the lubrication between the tool and the steel part, to assure a good steel machinability[5]. SUM 24L, which is SUM 23 plus lead, being naturally superior in machinability than SUM 23, is not simply replaceable by SUM 23. This is to say that the development of lead-free free-cutting steel means the development of a technology that can play the role of lead in steel. Such a technology is especially required to assure a high-precision machined surface (surface roughness) of lead-free steel not inferior to that of lead free-cutting steel.

The effect of a buildup of metal deposits sticking to the tool (which is called "built-up edge", or BUE) formed during cutting is known to be high in the machining of relatively soft free-cutting steel such as a low-carbon free-cutting steel[6]. In other words, a built-up edge (BUE) grows on the tool tip and works as a substantial part of the tool. But its sticking being not hard enough, BUE repeats growth and drops, and part of a dropped BUE can impair the surface roughness of the workpiece being machined. The control of this BUE was the largest technical problem to be solved.

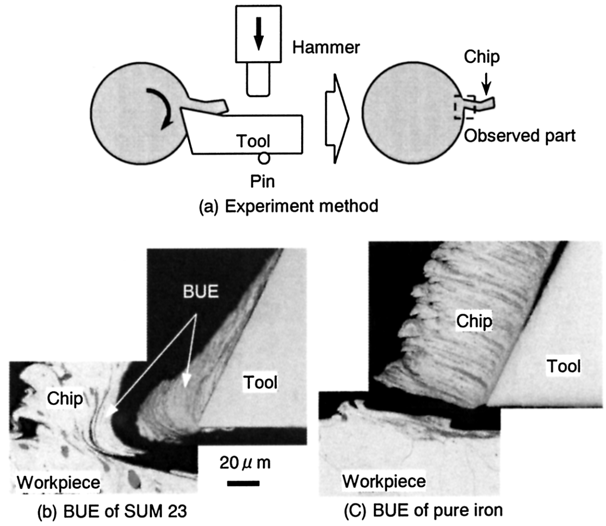

Fig. 1 Cross sectional view of chip formation part by QST

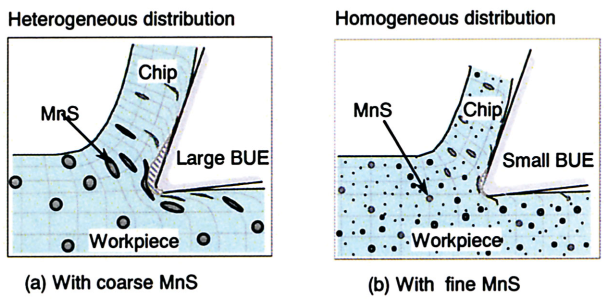

Fig. 2 Schematic view about effect of MnS on BUE formation

3. Concept of Built-up Edge Control

In the first step of our approach to the development of a new type of free-cutting steel, we clarified the surface forming mechanism of steel in cutting. **Fig. 1** shows cross-sectional views of parts of a workpiece and a tool where a chip and BUE are formed as observed in a quick stop test, QST. It is possible to observe the behavior of a chip being formed in a frozen state and of the formation of a built up edge by QST, in which the tool is drew back quickly. According to the findings by the observation, BUE is scarcely formed if the work-piece is a ferritic steel such as pure iron because adhesion is dominant, in spite of the fact that the steel is ductile. By contrast, if the work-piece is a resulfurized free-cutting steel containing coarse MnS and pearlitic structure, it assures a long tool life, but allows noticeable formation of BUE and is inferior to pure iron in terms of surface roughness. Closer observations of the cut surface revealed the cause of fracture by cutting to be a dimple formation, and we reasoned that the built-up edge grew with the secondary phase constituents such as MnS and pearlite[7].

Fig. 2 illustrates a schematic relation between MnS and BUE formation. Since cutting a homogeneous metal gives rise to a maximum stress in a metal portion nearest to the tool face, a chip separation occurs at a location closest to tool face. It has been known that MnS has an effect of reducing the resistance to cutting on account of stress concentration. It is reported that if a heterogeneous substance like MnS exists in a steel, cracking arises out of the heterogeneous part on account of stress concentration to eventually separate a chip[8]. With this in mind relative to the distribution of MnS, we can reason that the presence of coarse MnS as in Fig. 2 causes to separate a chip at a location somewhat away from the tool by the effect of stress concentration, leaving a part of the work-piece, in the area between the chip separation point and the tool, to remain on the tool as a built-up edge. Thus, it is reasoned, if MnS particles are very small and uniformly distributed as shown in Fig. 2 (b), the effect of stress concentration is small and the chip separation point is close to the tool face, leaving a small built-up edge to remain on the tool.

The above-discussed study led us to believe that we might be able to restrain the formation of built-up edge on the tool by homogenizing the microstructure of steel so as to cause to frequently give rise to dimples near the tool.

For steel containing lead, we can develop its good machinability by restraining the growth of the built-up edge by causing it to frequently come off, without impairing the surface roughness, because the lead in the steel has an effect of brittleness in the ferrite-phase structure in addition to a lubricating effect. To develop a lead-free steel, therefore, we not only chose to increase sulfur content, but also attempted to cause the built-up edge to frequently drop as well as to reduce the effect of stress concentration, while maintaining a lubricating effect by homogenizing the microstructure as much as possible through uniform distribution of fine MnS particles.

4. Features of the Developed Steel

4.1 Microstructure of the developed steel and built-up edge

Table 2 compares the hardness of the developed steel, used in our machinability evaluation, with that of other steels. The developed steel has a hardness almost equivalent to that of other low-carbon free-cutting steels, but has a higher sulfur content and contains MnS which is distributed in very fine particles through controlled manufacturing conditions. **Fig. 3** shows images of MnS observed by optical micrography and transmission electron micrography. Not only the MnS particles observed in the developed steel by an optical micrograph are smaller in size, but also those observed in that by the replica method of a transmission electron micrograph are much larger in number, than those in the other steels. Thus, the MnS in the developed steel is considered to assure homogeneous embrittlement and lubrication behavior, as well as to promote frequent drops of small built-up edges and to prevent the surface roughness from being deteriorated by the growth of the built-up edge. **Fig. 4** compares the observed built-up edges in the machining of the developed steel, SUM 23, SUM 24L, and a comparative steel containing the same percentage of sulfur as and larger coarse MnS particles than the developed steel.

Table 2 HV hardness of workpieces

Grade	Hardness HV
SUM 23	113
SUM 24L	113
Developed steel	105
Comparative steel with coarse MnS	102

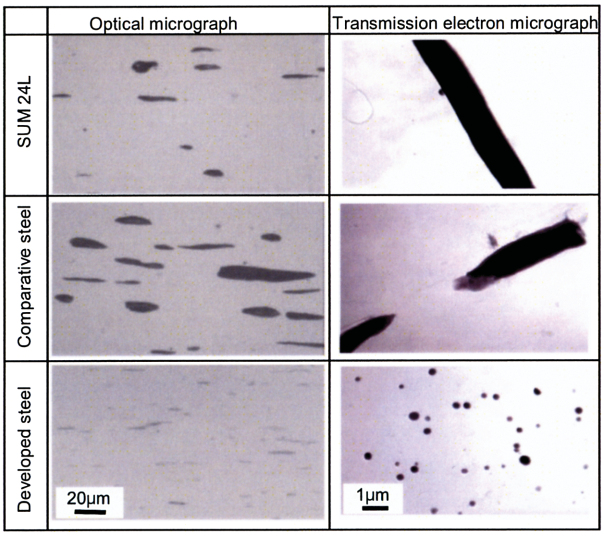

Fig. 3 Observation of MnS

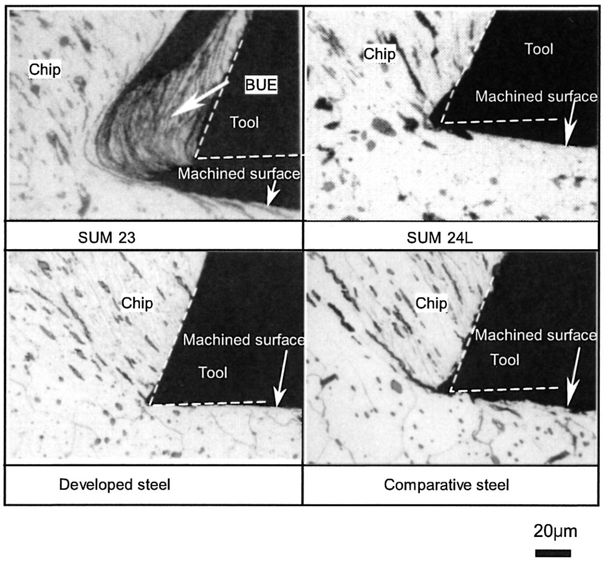

Fig. 4 Cross sectional view of chip formation by QST sample

4.2 Plunge cutting performance

For the purpose of evaluating the practical applicability of this developed steel, we tested the machinability of this steel in a simulated form of an actual part, i.e., an automotive hydraulic part and observed the surface roughness of its cut surface, the flank wear of the tool, and the built-edge formation on the tool. The observation results of the surface roughness relative to the number of machined parts are shown in **Fig. 5** (a), the flank wear relative to the number of machined parts in (b), and the built-up edge on the tool in (c). Thus the developed steel, when 800 parts made of it were machined, showed better surface roughness and tool flank wear than SUM 23 and equal to or better machinability than leaded free-cutting steel SUM 24L. For reference, the comparative steel having the same sulfur content and large coarse MnS was superior to SUM 23 but inferior to SUM 24L. The tool observation of the developed steel parts also showed little tool wear and little built-up edge formation. Seeing that the cutting operation of low-carbon steel is generally performed without operator and that the machining of 800 parts will usually takes a time length of nearly half of a day's work, the developed steel will surely be practicable industrially and can replace SUM 24L.

4.3 Drilling performance

Fig. 6 shows the maximum peripheral speed of drills vs. the total depth of drilled hole up to the end of the drill life, under the drilling conditions shown in the figure. The higher the drilling speed, the shorter the total drilled hole depth, usually. The depth of hole that can be made in the developed steel is nearly same as but slightly shorter than that in SUM 24L, and is much longer than that in SUM 23.

4.4 Longitudinal turning performance

Fig. 7 (a) shows the longitudinal turning time vs. the tool flank wear, and Fig. 7 (b) the turning time vs. the surface roughness, under the turning conditions specified in the figure. The turning was performed at a high speed, so built-up edge was scarcely formed. As a result of the performance test, the tool flank wear by the developed steel was smaller than by SUM 24L. The surface roughness at the turning speed of 800 sec. appeared inferior, possibly due to the effect of the tool flank wear.

Fig. 8 shows an equation for the geometrically calculated surface roughness of an ideally cut surface by a tool under certain cutting conditions. This equation suggests that the cut surface roughness becomes smaller as the tool wear progresses with increasing tool nose radius, and presumably indicates that the surface roughness of SUM 24L at 800 sec. was superior because the tool wear progressed to increase Rc, not because it reflected the machinability of the steel. Refer to **Fig. 9** in this respect. Fig. 9 compares the cut surfaces, tool wear and chips of SUM 23, SUM 24L and the developed steel. Feed marks were seen in the cut surfaces, and tear marks were seen in the cut surface sections between the feed marks. The degrees of the

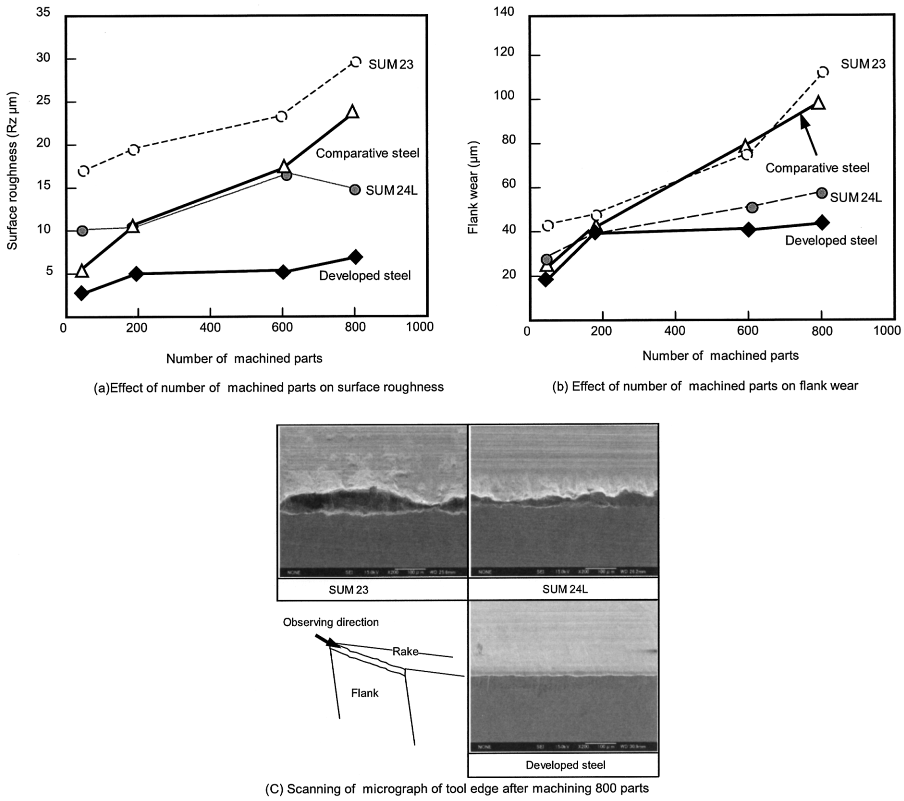

Fig. 5 Effect of number of machined parts on surface roughness and flank wear

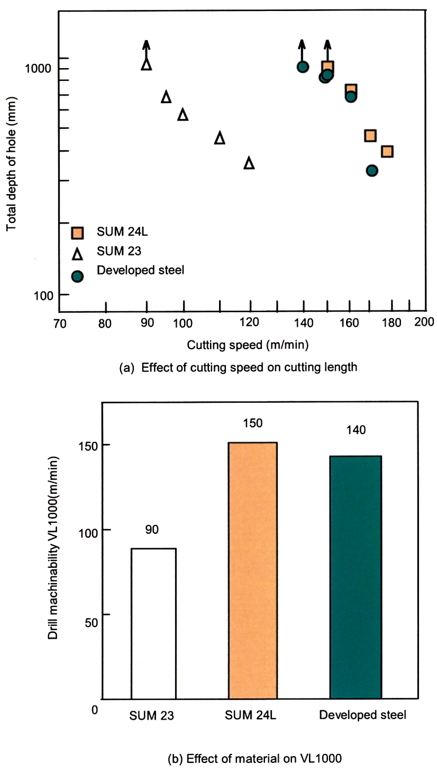

Fig. 6 Drill machinability

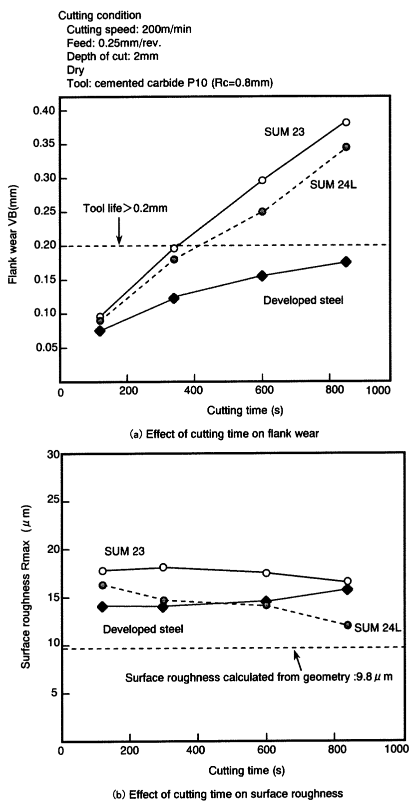

Fig. 7 Turning machinability

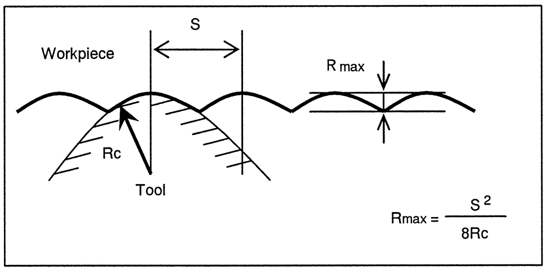

Fig. 8 Surface roughness calculated on geometry

tears were smallest in the developed steel, and higher in SUM 24L and then in SUM 23. The tool wear was also smallest by the developed steel, and the chips were similar between the developed steel and SUM 24 to show no problem for practical steel application. Thus, the developed steel was superior to the other two steel grades as far as the cutting performance is concerned.

The developed steel is produced through melting in the converter and the bar and wire rolling lines at the Muroran Works. Low-carbon free-cutting steel is generally supplied through wire drawers to automobile, OA equipment, and household electrical appliance manufacturers. It is particularly used for small parts for varieties of applications such as oil-sealing parts, bearing mounting parts, and parts whose fitting to mating parts has major importance. This developed steel is also supplied to users through similar routes. So far, the properties of this steel, including wire drawability and platability, and excluding machinability, are comparable to or better than those of conventional steels, and this steel is appreciated as replaceable to SUM 24L.

5. Conclusion

We have reported above the lead-free low-carbon free-cutting steel which we developed with a view to replacing free-cutting steel containing lead, for the purpose of reducing the use of an environment polluting substance. Global regulations to control lead in steel are expected to be enforced more rigidly and in wider scope. Seeing that low-carbon free-cutting steels have been much used in familiar products, greater importance will be attached to products more friendly to the environment. Nippon Steel has taken positive steps to face the task of reducing lead in steel. We believe the developed steel reported here is gentle to the environment and cost-effective to steel users and is expected to be used more in future.

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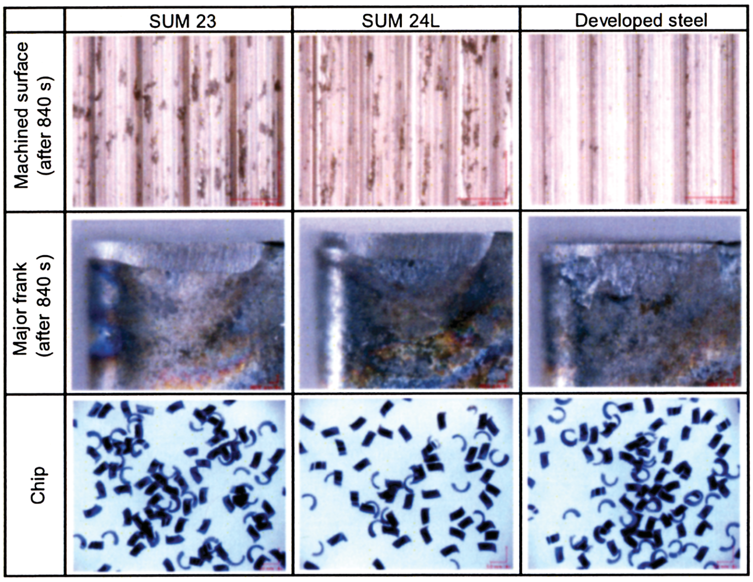

Fig. 9 Optical micrograph of machined surface, tool wear, and chip