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Free cutting steel consists of two types, one for machine structural use and the other based on low carbon steel for hard cutting, such as SAE 12L14. Conventionally, Pb has been added to free cutting steels to improve their machinability, but Pb in steel is thought to have a harmful effect on the human body. Therefore, as alternatives to Pb addition in free cutting steels, JFE Steel and NKK BARS & SHAPES studied graphite precipitation in the steel and control of the sulfde morphology by the chemical composition and developed new Pb-free free cutting steels based on these respective concepts. In the graphite-type free cutting steel for machine structural use, JFE Steel realized machinability equal to that of the Pb-added steel by controlling the state of existence of C in the st[illegible]el, and achieved an excellent balance of cold workc[illegible]lity and high fatigue strength after quenching and [illegible]pering. As a substitute for the low carbon Pb-add[illegible]ee cutting steel (SAE 12L14), NKK BARS & SH[illegible]eveloped a steel with improved machinability by [illegible]llizing large sulfde inclusions, which is realiz[illegible] increasing S addition while also adding Cr on [illegible]sis of the estimation from the calculated phase [illegible]ns.

1. Intr[illegible]on

F[illegible]ing steels with Pb addition are widely used as [illegible]s for automobile and industrial machinery pa[illegible]wever, in recent years, the use of Pb has been [illegible]red a problem from the viewpoint of environmental protection.

Free cutting steels can be broadly classifed into two types, (1) a free cutting steel for machine structural use, in which cold forgeability and high strength, are required simultaneously with machinability, and (2) so-called low carbon free cutting steels, in which machinability with a low carbon composition is the primary requirement, as represented by SAE 12L14.

As alternatives to Pb addition for improving machinability, JFE Steel and NKK BARS & SHAPES developed free cutting steels by utilizing graphite precipitation in the steel and controlling the sulfde morphology by the chemical composition of the steel, corresponding to these respective applications. This paper introduces these steels.

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and cold forgeability without Pb addition to the steel has been desired.

Based on this background, a free cutting steel which possesses high fatigue strength and does not require Pb addition had been strongly desired. The key point for realizing a material with these features was to discover some means of improving machinability without reducing fatigue strength.

In this development, as an alternative to Pb addition and inclusion control by free cutting additives, control of the state of C existing in the steel was studied as a completely unprecedented factor for improving machinability. The most important feature of this development is that C which normally exists in steel in the form of cementite is changed to graphite. However, in steels for machine structural use, which have a hypoeutectoid composition, industrial use of graphite had been diffcult with the conventional technology.

This chapter describes the chemical composition for enabling industrial graphite precipitation and its effect on the properties of steel for machine structural use.

2.2 Concept of Development

2.2.1 Use of graphite to improve machinability-fatigue strength balance

The concept of utilizing graphite in the developed steel is shown schematically in **Fig. 1**. Changing hard cementite to graphite makes it possible to soften the steel and thereby improves machinability. Machinability is also substantially improved by the lubricating action of the graphite on the tool surface. On the other hand, because graphite particles are redissolved into the matrix

2.2.3 Increase in number of graphite nucleation sites utilizing BN

Fine dispersion of graphite particles in steel is effective both for preventing deterioration of fatigue strength and for shortening the graphitization time. To achieve fine dispersion of graphite particles, it is necessary to increase the number of nucleation sites. In this development, acceleration of graphite nucleation by precipitates in the steel was studied. Although nucleation of graphite particles was accelerated by the existence of various types of precipitate in the steel, BN was an extremely effective nucleation site.[3,4)]

In addition to the crystallographic structure of the precipitates, graphite and BN also bear an extremely close resemblance in terms of their precipitation modes.

strength exceeding 500 MPa after quenching and tempering. In comparison with the size of the inclusions in the conventional free cutting steel, which is on the order of several 10s of micro meter, the graphite particles are fne, at several micro meter, due to the increase in the number of nucleation sites using BN. Furthermore, the graphite in the steel dissolves into the steel matrix due to heating during quenching. It should be noted that, although unsolved BN also exists in the developed steel, its size is about 1 μm. Thus, because the graphite and BN used in the developed steel are both fne, unlike the conventional inclusions, they are thought to have no negative effect on fatigue strength.

The developed steel can be used in a wide range of applications in steel for machine structural use, centering on parts where the conventional Pb-added steel had been used and cold forging applications where machinability is a problem and high strength had been diffcult to realize.

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containing 0.3% Pb and 0.3% S. In automotive applications, it is used in large quantities in transmission oil hydraulic control valves and oil hydraulic hose con-

ably high oxygen content, on the order of 150 ppm, it was considered diffcult to improve its machinability by adding Ca or B, which is already used in the steel for machine structural use. Therefore, because it was necessary to conceive a different method, the authors studied S, which is added in large quantity as an element which improves machinability. It has long been known that the machinability of S-added free cutting steels is improved as the size of sulfde inclusions becomes larger.[7] Therefore, the improvement of machinability by forming large sulfde inclusions was studied from this viewpoint. Because the construction of thermodynamic databases for sulfdes has proceeded rapidly accompanying a progress in microalloying technology, this type of database was effectively used in this study.

For the developed steel, frst, a phase diagram was obtained by the phase equilibrium calculation of a multicomponent alloy system, and the alloy composition with which large sulfde inclusions could be expected was predicted. Based on the results, confrmation tests were actually conducted, including melting and machinability tests, to decide the alloy composition, and a new Pb-free free cutting steel was developed. The authors wish to note that this new material was developed jointly with Prof. Kiyohito Ishida of Tohoku Univ. and Senior Researcher Katsunari Oikawa of AIST Tohoku: National Institute of Advanced Industrial Science and Technology.

3.2 Concept of Developed Steel

3.2.1 Prediction by phase diagram calculation

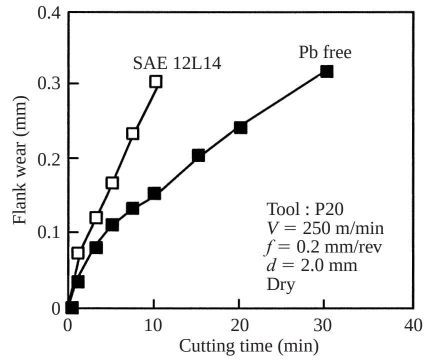
The sulfde inclusions which contribute to machinability are crystallized by a monotectic reaction during solidifcation of the molten steel.[8] When considering the methods for securing large sulfde inclusions, the following methods are conceivable:

(1) Crystallization of large sulfde inclusions in the solidifcation stage
(2) Reduction of the forging ratio after crystallization

In case of (1), the reduction of solidifcation rate is a general method, and increasing the casting cross-sectional profle or slow cooling during casting is conceivable. However, in both methods, it is diffcult to effect large changes in the current continuous casting process. On the other hand, in case of (2), if the production of rolling materials of the same size is considered, the reduction of forging ratio by using a smaller casting cross-sectional profle is conceivable. However, as mentioned previously, adoption of a small casting cross-sectional profle results in the reduction in the size of inclusion during casting, and thus would have little effect. The authors therefore believed that a composition system which expands the temperature range in which

oped steel.

As described above, the 1%Cr-0.4%S steel was adopted as the Pb-free free cutting steel as a result of confrmation tests with experimental melting furnace steel



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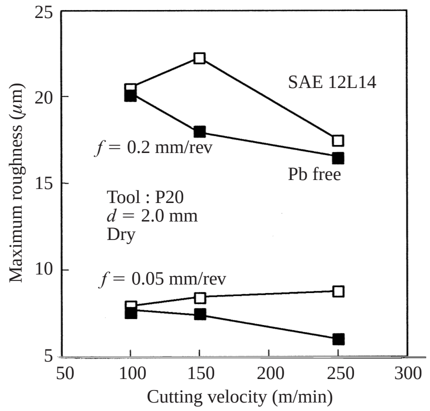

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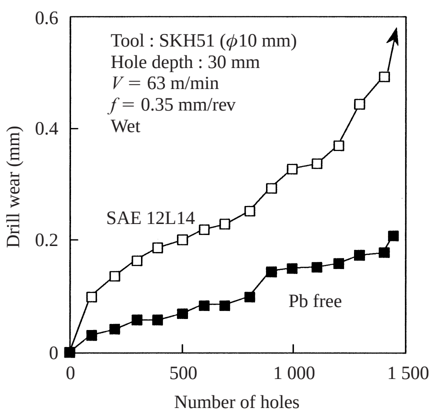

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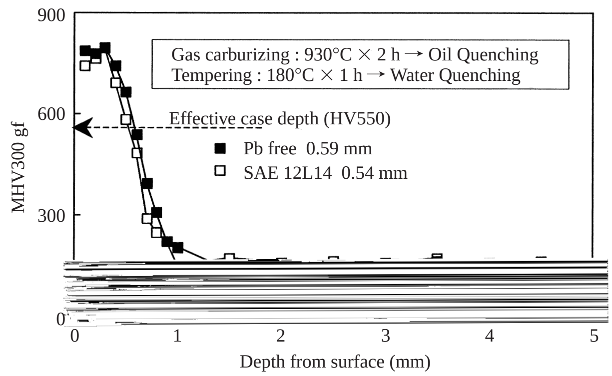
4. Conclusion

This paper has introduced two new Pb-free free cutting steels, a free cutting steel for machine structural use and a substitute for SAE 12L14, which were developed in response to customers' needs from the viewpoint of global environmental problems.

The graphite-precipitation type Pb-free free cutting steel for machine structural use contains no substances which are harmful to the environment and possesses excellent machinability and cold forgeability, amply satisfying the property requirements of steel for machine structural use.



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The SAE 12L14-substitute Pb-free free cutting steel features improved machinability by large sulfde inclusions. This was possible for the frst time by adding Cr and further increasing the S content based on the estimation from the calculated phase diagrams.

With the increasing trend toward green procurement in all industries, there is a tendency to reduce the use of Pb. To meet this need, JFE Steel and its group companies will continue to develop new products to ensure that these Pb-free free cutting steels can be used in a variety of felds.

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