KAWASAKI STEEL TECHNICAL REPORT
No.8 (September 1983)

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Synopsis :
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1 Introduction

Along with the rapid development of the high-speed automated machining techniques, demands have been increasing for free cutting steels of good quality for machine parts. In fact, not only good machinability but also fitness for cold heading is a growing requirement recently for free cutting steels. Kawasaki Steel Corporation has established a technique to produce low-carbon resulfurized free cutting steels satisfying both machinability and cold forgeability, utilizing the features of continuous casting process. The present report discusses technical developments, including problems in the continuous casting of resulfurized free cutting steels and the features of steel products manufactured by this technique, such as machinability and cold forgeability.

2 Problems in and Development of Continuous Casting of the Steels

The machinability of resulfurized free cutting steels, one of the most important properties, is known to be affected extensively by the shape of sulfide[1]. It is said that the oxygen content in steel must be controlled at 200–300 ppm[2] for obtaining sulfides of spindle form which give favorable machinability. Since the oxygen content of this level is highly harmful with respect to the blowhole generation at the time of solidification and deteriorates the surface properties of the product, it constituted one of the greatest prohibitive factors for the promotion of continuous casting. Moreover, the high oxygen content causes secondary problems such as damage of refractory materials and deterioration of powder. Checking of these problems and contriving their countermeasures constitute the important task for determining the feasibility of the production of resulfurized free cutting steel through the continuous casting process.

2.1 Suppression of Blowhole Generation

The addition of deoxidizing elements such as Si and Al to the resulfurized free cutting steels must be avoided because of machinability requirement[3]. If the deoxidation is insufficient, blowholes generate under the bloom surface. R.B.G. Yeo[4] demonstrated the division of rimmed and killed regions of resulfurized steel on the basis of S and Mn concentrations,

* Originally published in *Kawasaki Steel Giho*, **15** (1983) 3, pp. 31–37
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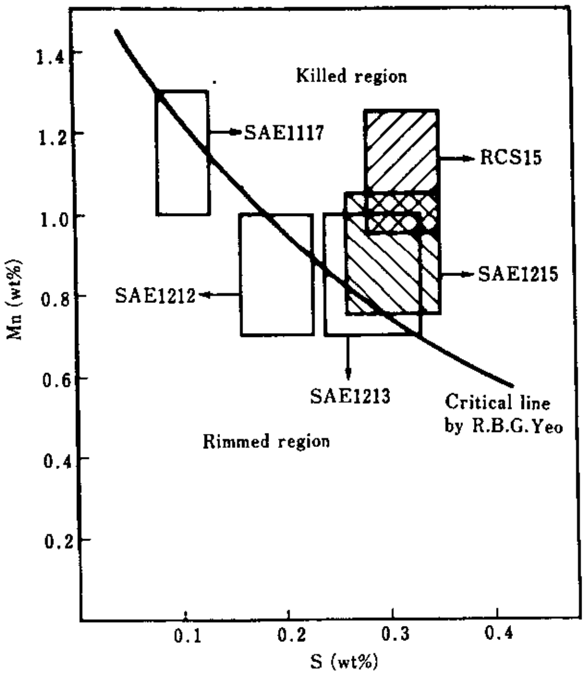

Fig. 1 Relation between Mn and S contents on rimming

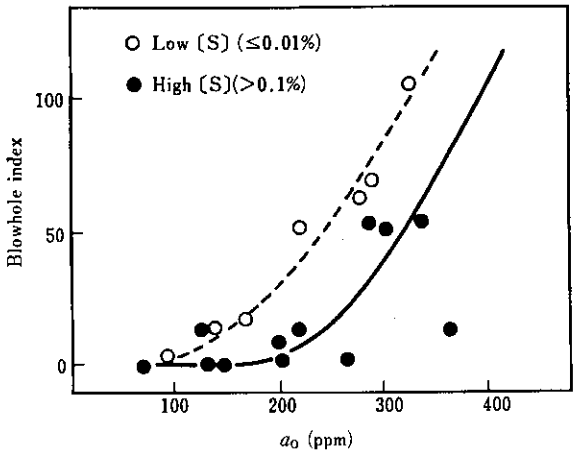

Fig. 2 Influence of oxygen activity, a_O, on blowhole generation

as shown in **Fig. 1**. The range of composition of the free cutting steel produced by the Kawasaki Steel Corporation is indicated in **Fig. 1**. SAE1213 and SAE 1215 which are each to be produced through the continuous casting process partly belong to the rimmed region. For this reason, in order to check the limits of blowhole generation at the bloom surface of these two types of steels, the blowhole occurrence was examined in steel solidified around the steel rod inserted into the molten steel with the content of Mn fixed at 0.90% and S and O varied in 0.003–0.300%

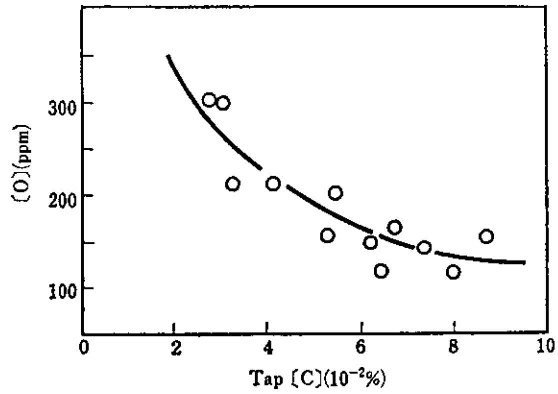

Fig. 3 Relation between [C] at tapping and [O] in tundish

and 100–300 ppm, respectively. The relationship between the free oxygen contents (a_O) in molten steel and the blowhole generation is shown in **Fig. 2**. When [S] is greater than 0.100%, the blowhole generation is suppressed at a_O less than or equal to 200 ppm[5]. In the high-S and high-O molten steel such as resulfurized free cutting steels, a_O nearly coincides with the oxygen contents in steel (O_T). If the oxygen content can be controlled at 100–200 ppm by Tap [C] shown in **Fig. 3**, the blowhole generation is suppressed.

2.2 Prevention of Erosion of Immersed Nozzle

The composition of resulfurized free cutting steel is markedly unfavorable in inhibiting erosion of refractories. Particularly, the erosion of immersed nozzle not only poses problem in continuous casting, but also affects the quality unfavorably. With regard to the erosion resistance of immersed nozzle, nozzles mainly composed of SiO_2, Al_2O_3 and ZrO_2 were compared. The relationship of erosion extent and S content in molten steel is shown in **Fig. 4**. The erosion of Al_2O_3- and ZrO_2-including nozzles is less extensive and

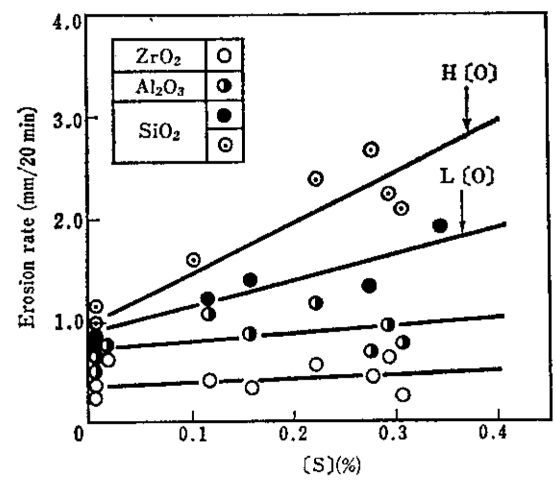

Fig. 4 Effect of [S] on erosion rate of immersed nozzle

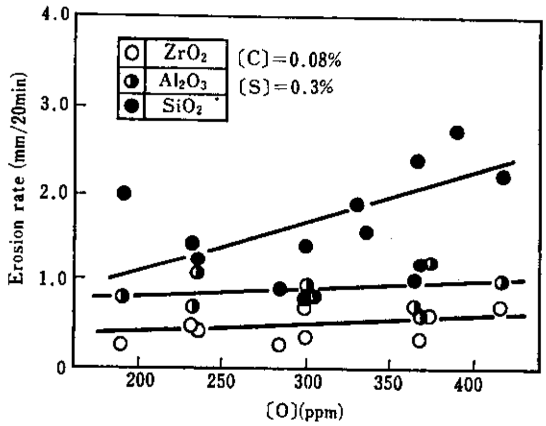

Fig. 5 Effect of [O] on erosion rate of immersed nozzle

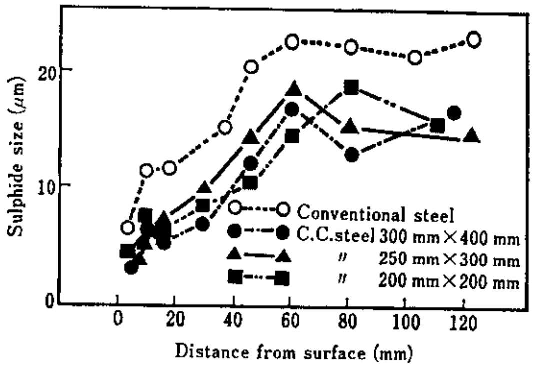

Fig. 6 An example sulfide size variation in continuous cast steel with distance from surface

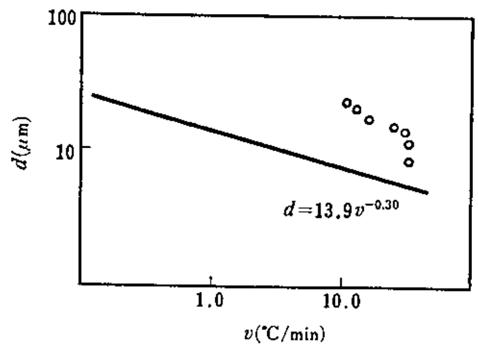

Fig. 7 Relation between average size of sulfide, d, and cooling rate of solidification front, v, in bloom

constant irrespectively of S content. On the other hand, the erosion of SiO_2-containing nozzle increases with the S content, and when the S content is 0.300%, the erosion becomes 5 times as much as that of ZrO_2-containing nozzle.

Moreover, the erosion is affected also by the oxygen content, tending to increase with the oxygen content as shown in **Fig. 5**. It is supposed that the SiO_2-containing nozzle is readily affected by surface active elements, S and O, because the nozzle has greater wetting property with molten steel and MnO-SiO_2 layer of low melting temperature is formed on the surface. It is desirable, therefore, to use the immersed nozzle made from erosion-resistive ZrO_2-containing material in view of both continuous casting and product quality[6].

2.3 Shape of Sulfides

Shape, composition, quantity and distribution of sulfides are counted as main factors to determine the machinability of resulfurized free cutting steels, and these factors are affected by the solidification conditions. The distribution of sulfide's average diameters in bloom is shown in **Fig. 6**. The sulfide size in continuously cast steel is somewhat smaller than that in conventional steel. This may be attributed to smaller cross section of continuous casting mold than that for ingot, and faster solidification.

Figure 7 shows the relationship between the cooling rate at the solidifying point and the average diameter of sulfide particles, revealed by the analysis of two-dimentional heat transmission through the difference calculus. While the average sulfide diameter of 10–15 μm at cooling rate of 10–30°C/min was slightly larger than the values reported by Takada et al.[7], the tendency of sulfide particle size growing at a smaller cooling rate was recognized.

However, as is evident in **Fig. 6**, the sulfide particle size was affected less extensively by the mold size. This may be attributed to a smaller difference in cooling rate for different mold size in the normal operational conditions of continuous casting, which failed to provide significant difference in sulfide particle size.

3 Quality of Continuous Cast Steel

3.1 Internal and Surface Properties

The relationship of sulfide shape in the product steel bar to the total oxygen content in steel is shown in **Fig. 8**. While it is said that the oxygen content required for obtaining spindle-shaped sulfide, which is favored for machinability, is 200–300 ppm in the case of ingot steel, the oxygen content to require similar sulfide shape ratio in continuous cast steel is 100 ppm or greater. Hence, it is possible to reduce the oxygen content of steel[8]. This may be attributed to less chance for elongation of sulfide owing to the much smaller reduction rate in the continuous cast steel than in the ingot steel.

Moreover, in the case of ingot steel, surface defects and macro-streak flaws may occur frequently owing to $MnO\text{-}SiO_2$ inclusions in association with the blowhole generation or erosion of refractories, since the oxygen content is to be set at 200 ppm or greater in consideration of sulfide shape. These defects cause cracks in the process of cold drawing, cold forging or cutting of the product. **Figure 9** shows the relationship between the oxygen content and the index of surface defect of the product evaluated by the magnetic inspection. It is evident that in the case of continuously cast steel, the excellent surface conditions can be obtained by controlling the oxygen content to 150 ppm or so.

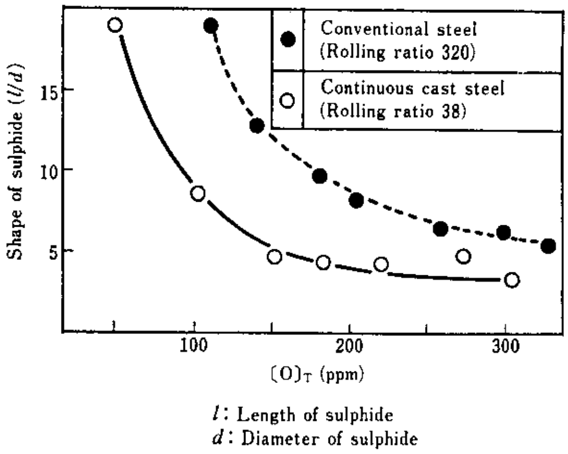

Fig. 8 Relation between $[O]_T$ and shape of sulfide

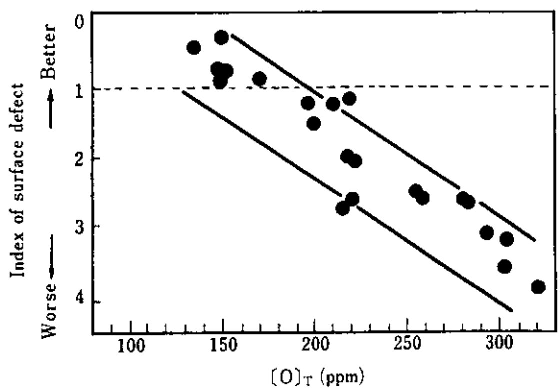

Fig. 9 Relation between $[O]_T$ and index of surface defect

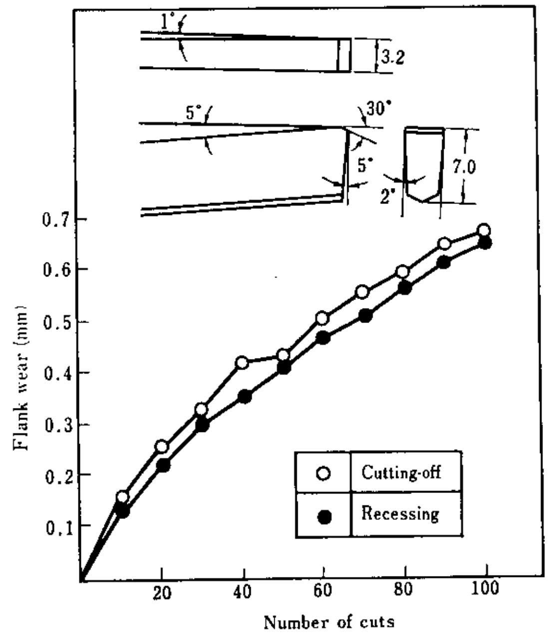

Fig. 10 Relation between number of cuts and flank wear (Tool: P20)

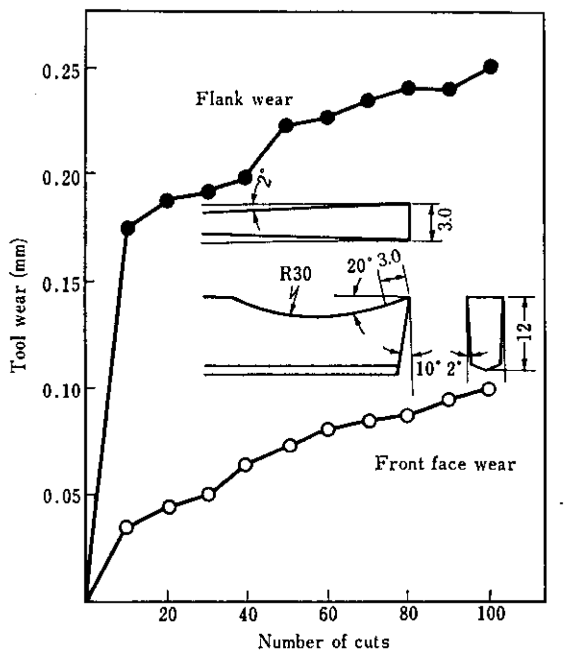

Fig. 11 Relation between number of cuts and tool wear (Tool: SKH4)

Table 1 Machinability test and conditions

Machinability test	Turning test		Cutting-off test	
Tool	P 10	SKH 4	P 20	SKH 4
Tool profile	−5, −5, 5, 5, 15, 15, 0.8	−5, 15, 5, 5, 15, 15, 0.8	See Figs. 10, 11	
Cutting speed, V (m/mm)	140～300	80～140	16～100	20～80
Feed, f (mm/rev.)	0.25	0.25	0.10	0.10
Depth of cut d (mm)	2.0	2.0	—	—
Cutting fluid	Dry	Dry	Dry	Wet

3.2 Machinability

The machinability was evaluated by the turning test and the cutting-off test, using carbide tools and high speed steel tools (H.S.S. tools). The test conditions are given in **Table 1**. In the cutting-off test, the tool profile was determined by reference to the testing method described by Narutaki et al.[9,10] **Figures 10** and **11** show the tool wear property revealed by the cutting-off test by the use of carbide and H.S.S. tools. Since the front face wear was nearly unrecognizable in the former, the tool wear property was evaluated on the basis of flank wear. While the front face wear grows linearly with the increase in the number of cuttings in the latter, the flank wear proceeds markedly in the initial stage to make the measured value instable. So, the tool wear property was evaluated on the basis of front face wear.

3.2.1 Machinability of rolled steel bar

The machinability of continuous cast steel and ingot steel evaluated by the turning test is given in **Fig. 12**. It is evident that both continuous cast steel and ingot steel have identical machinability. **Figure 13** shows the test results at various radial positions of the product steel bar. The machinability of continuous cast steel is not reduced in comparison with that of ingot steel, in spite of fine sulfide under the surface[11].

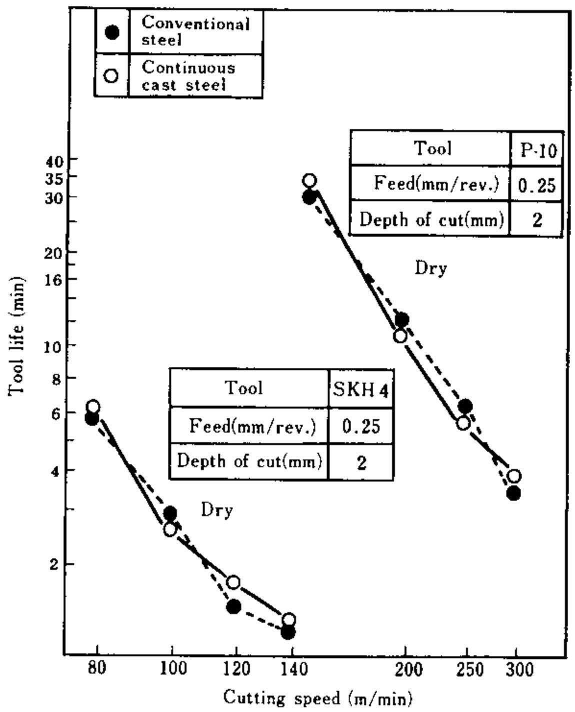

Fig. 12 Comparison of V-T curves in turning test between conventional and continuous cast steel

The effect of sulfide on machinability during machining is attributed to the concentration of internal stress at the chip shearing region and to the boundary lubrication with viscous fluid between the tool and chips. It is generally claimed that the former effect is greater in case of resulfurized free cutting steel[1].

The identical machinability in continuous cast and ingot steels is attributed to the fact that spindle-shaped sulfides can be realized stably in the former despite generally smaller sulfide size. Moreover, the maintenance of good machinability at the fine sulfide zone in the surface layer of continuous cast steel may be interpreted on the basis of reduced mean free path among sulfides owing to the uniform distribution of numerous sulfide particles.

3.2.2 Machinability after cold drawing

In order to check the machinability of cold drawn steel rod manufactured through the continuous casting process, specimens were drawn at four levels of area reduction, 5–24%. As for the mechanical properties of drawn steel rod, it is generally recognized that as the area reduction increases, hardness and strength rise, while ductility and toughness diminish.

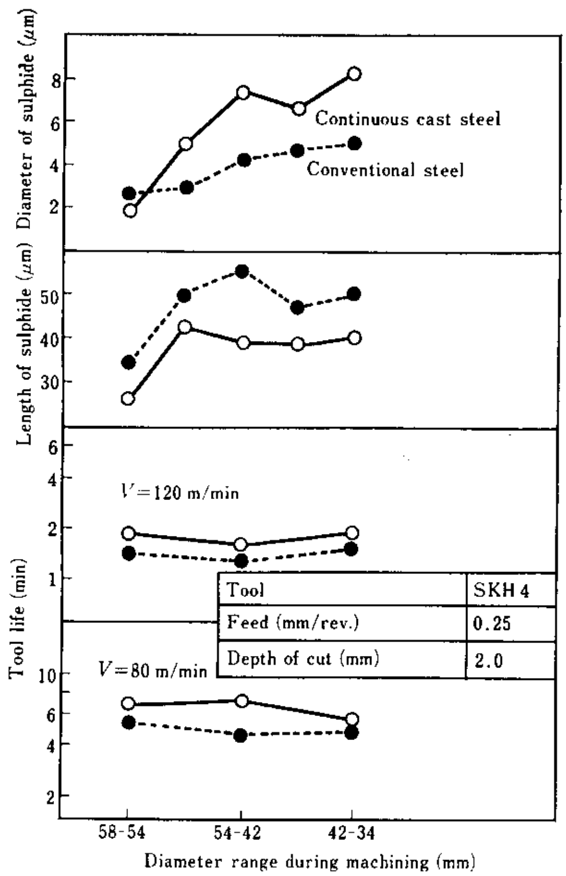

Fig. 13 Radial distribution of sulfide shape and tool life in ϕ60 mm specimen

The relationship between area reduction and the tool life evaluated through the turning test using H.S.S. and carbide tools is shown in **Figs. 14** and **15**. In the test using H.S.S. tool, the greater the area reduction, the longer the tool life, for any cutting speed. On the contrary, when carbide tool was used, the greater the area reduction, the shorter the tool life. The reduction of ductility after drawing suppresses wear of H.S.S. tool by promoting the development of voids and microcracks in the chip shearing face. When carbide tools are used, the temperature of cut-shearing face rises as the cutting speed in this experiment is faster than 140 m/min, therefore, the mechanical properties are recovered to the original level, cancelling the effect of drawing[12].

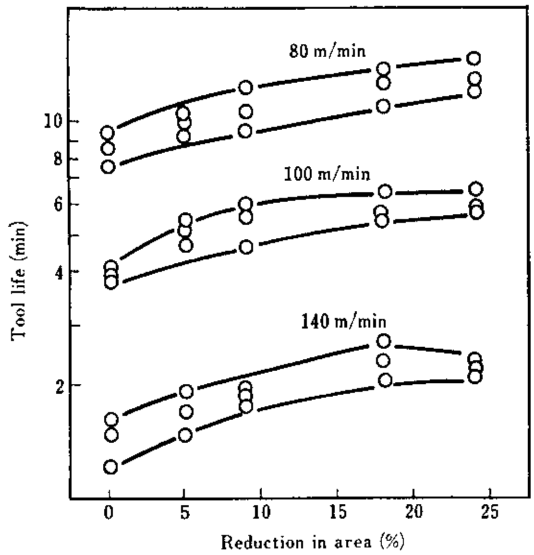

Fig. 14 Influence of cold drawing on tool life in turning test (Tool: SKH4)

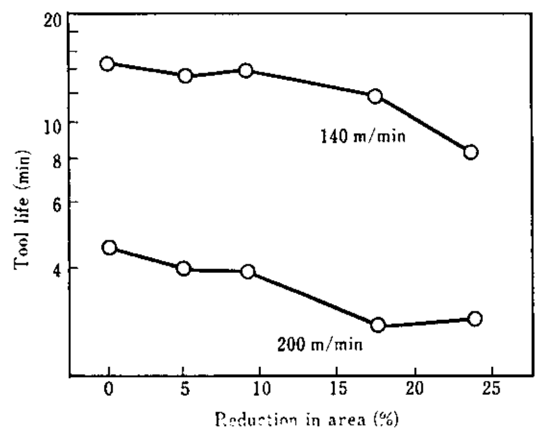

Fig. 15 Influence of cold drawing on tool life in turning test (Tool: P10)

As shown in **Fig. 16**, the faster the cutting speed and the greater the area reduction, the smaller the chip thickness became, for both H.S.S. and carbide tools.

Figure 17 shows the surface roughness. The greater the area reduction, the smaller the surface roughness (R_{max}) became. While the surface roughness became smaller as the machining by carbide tool progressed, no temporal changes was recognized in surface roughness in case of using H.S.S. tool.

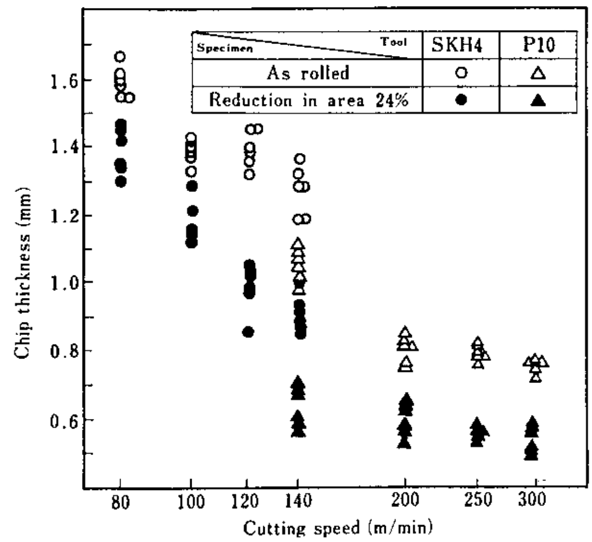

Fig. 16 Relation between cutting speed and chip thickness in turning test

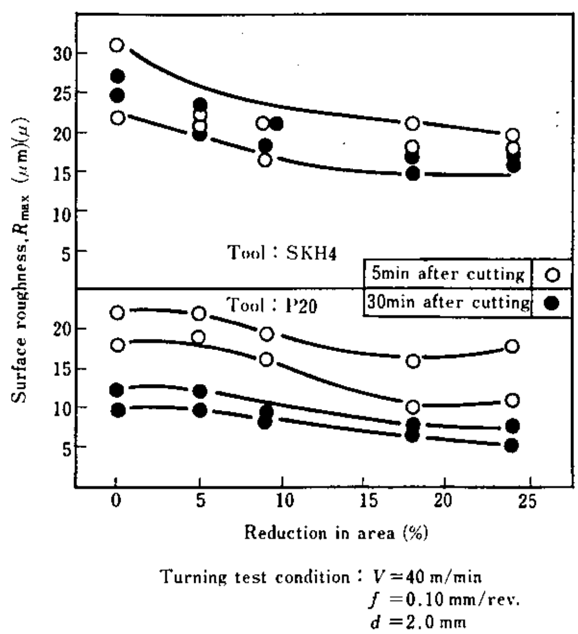

Fig. 17 Relation between reduction of area and surface roughness, R_{max}

The reduced ductility caused by drawing acts favorably on the surface roughness and chip thickness. Particularly, with the carbide tool in which the build-up edge is generated less extensively than in the H.S.S. tool, the chip thickness and surface roughness are held smaller.

The results of cutting-off test with H.S.S. and carbide tools are shown in **Figs. 18** and **19**. For both types of tool, the greater the area reduction, the smaller the tool wear. In the case of cutting-off test, the tool wear was most outstanding at a peripheral

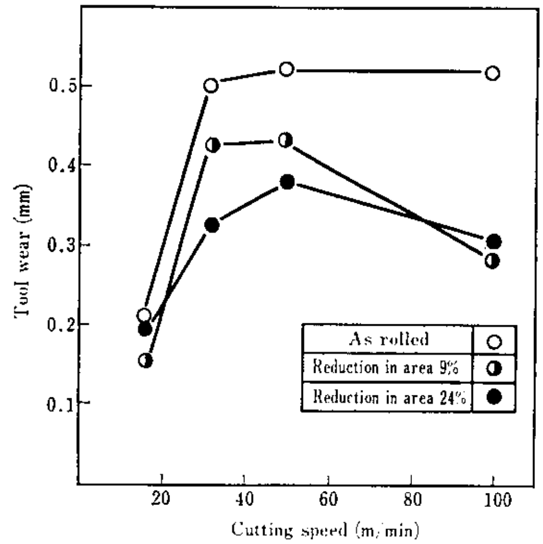

Fig. 18 Influence of cutting speed on tool wear in cutting-off test (Tool: P20)

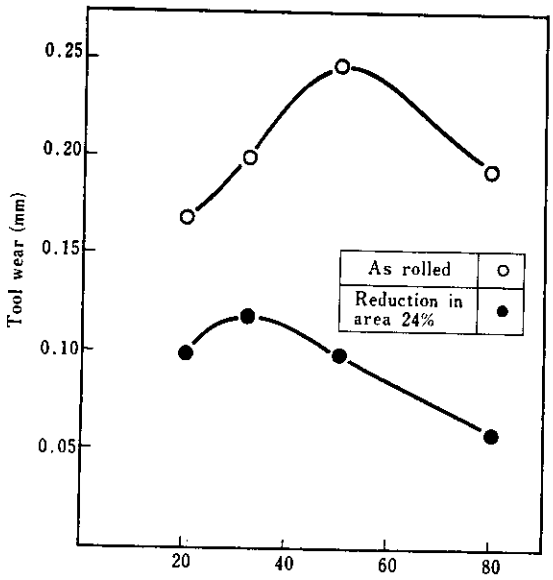

Fig. 19 Influence of cutting speed on tool wear in cutting-off test (Tool: SKH4)

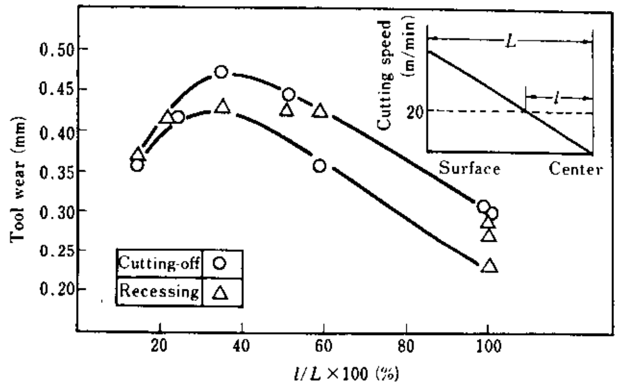

Fig. 20 Relation between l/L and tool wear in cutting-off test (Tool: P20)

speed of 50 m/min or so. This phenomenon was examined in relation to build-up edge. It is said that the build-up edge is generated in the region of low speed cutting[13].

Figure 20 shows the relationship between tool wear and low speed cutting ratio (l/L in **Fig. 20**; in the range of radius l, the cutting speed is 20 m/min or slower) in cutting-off work. When cutting is made always in a low speed region, build-up edge is formed stably to suppress tool wear. When the low speed cutting takes 40% or so of total cutting, build-up edge is repeatedly generated and removed to accelerate tool wear. If the ratio is smaller than 40%, the frequency of build-up edge generation declines, suppressing wear at the time of drop-out[14].

3.3 Cold Forgeability

While the cold forgeability and the machinability are generally said to be incompatible each other, the cold forgeability is often demanded recently for the resulfurized free cutting steels. The cold forgeability of continuous cast steel was compared with that of ingot steel. The cold forgeability was tested in the static state by the use of the test method and specimens recommended by the Subcommittee of Cold Forging, Japan Society for Technology of Plasticity[15].

The results of the cold forgeability test are shown in **Fig. 21**. The continuous cast steel has greater upsetting limit than the ingot steel, and hence better cold forgeability. **Photo 1** shows the microstructure of crack after the cold forgeability test. The ingot steel includes more coarser sulfides in the surface layer than the continuous cast steel, and cracks occur at sulfides with relatively smaller strain, and grow as the strain increases while propagating along sulfides. On the other hand, the continuous cast steel with fine sulfides at the surface layer is less susceptible to cracks. **Figure 22** shows the effect of fine sulfide layer thickness

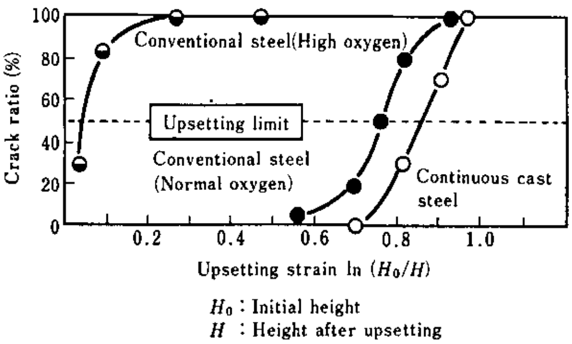

Fig. 21 Relation between upsetting strain and surface crack ratio of upset specimen

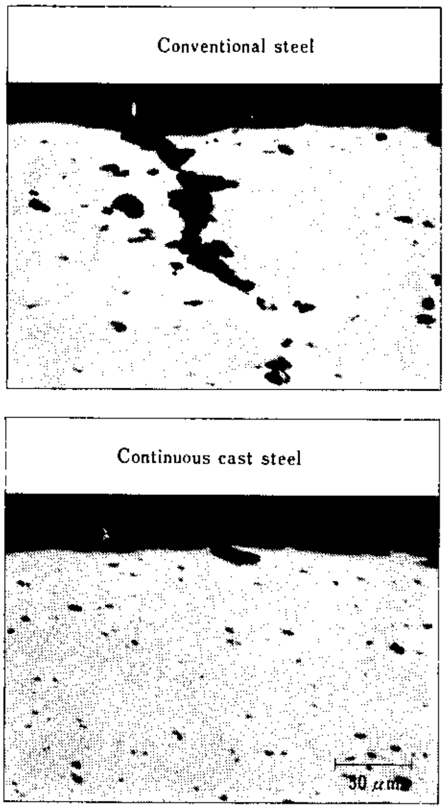

Photo 1 Typical micrographs of crack observed at cross section

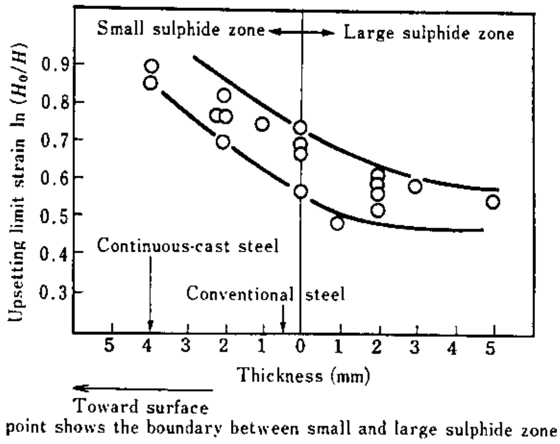

Fig. 22 Relation between upsetting limit strain and thickness of small sulfide zone at surface of specimen

(t_S) at the surface layer of specimen on the upsetting strain limit[11]. Since the cold forgeability is improved with the increase in t_S, superiority of continuous cast steels to ingot steels in the cold forgeability is thus explained.

Moreover, the cold forgeability is unfavorably affected by the oxide inclusions. Since the oxygen content in the continuous cast steel can be reduced, the content of oxide inclusion is so low that the cold forgeability is not reduced drastically, as in case of oxygen-rich ingot steel shown in **Fig. 21**.

4 Conclusions

Kawasaki Steel Corporation succeeded in producing low-carbon resulfurized free cutting steels through the continuous casting process, which had been regarded difficult previously. The main problems associated with the continuous casting are ① blowhole generation and ② erosion of refractories. The first problem was overcome by establishing the technology of controlling deoxidization, and the second problem by the selection of appropriate refractory materials, thus allowing the manufacture of sound bloom.

Since the reduction ratio of continuous cast steel is smaller than that of ingot steel from the raw material to the product, it is possible in the former to produce spindle-shaped sulfides even if the oxygen content is reduced, resulting in the reduction of oxide inclusions. For this reason, the machinability of continuous cast steel is the same as that of ingot steel. Moreover, the cold forgeability of continuous cast steel is extensively improved in comparison with that of ingot steel since the surface layer includes fine sulfide particles and there is little oxide inclusions. Though the machinability and the cold forgeability are said to be incompatible each other, it is possible to make both properties satisfactory by making steel through the continuous casting process. On the ground of the facts described above, the resulfurized free cutting steels manufactured by the continuous casting process are excellent in machinability and cold forgeability, and it is expected that this method will become the main stream process in future in view of energy saving and high productivity.

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