Study on the Machinability of Resulfurized Composite Free-Cutting Steels

D. Lou, K. Cui, and Y. Jia

The machinability of S, S-Ca, S-RE, and S-RE-Ca system resulfurized composite free-cutting steels were investigated, where RE is rare earths, mostly cerium. The experimental results showed that in the low cutting speed range (≤35 m/min), the S-RE system free-cutting steel had better machinability than the others and that the S-RE-Ca system free-cutting steel exhibited the best machinability at high cutting speeds. A protective layer capable of preventing diffusion wear was formed on the rake face of a P30 tool when S-RE-Ca system free-cutting steel was machined in the cutting speed range of 120 to 160 m/min.

Keywords
free-cutting steel, machinability, protective layer, resulfured composite system

1. Introduction

MACHINABILITY is an important criterion in materials selection and design for many applications. The strong influence of inclusions on the machining behavior in resulfurized or calcium-treated free-machining steels have been recognized for many years. It is well known that manganese sulfide inclusions in resulfurized free-cutting steel have deleterious effects on transverse properties of the steel after hot rolling. Consequently, free-machining steels with medium sulfur content (0.04 to 0.1 wt%) under inclusion shape control have been developed (Ref 1). For example, calcium treatment of steel has emerged as a viable and increasingly popular way of achieving a more desirable balance between machinability and service performance, but it is difficult to control steelmaking parameters to achieve the desired oxide species such as anorthite or gehelenite. Otherwise, calcium-treated steel can increase tool life only under high cutting speed (Ref 2).

For this reason, calcium, rare-earth (RE), and RE plus calcium additions to resulfurized free-machining steels with medium sulfur content (0.04 to 0.1 wt%) have been researched (Ref 3, 4). The experimental results showed that RE-treated and (RE + Ca)-treated resulfurized free-cutting steels are easy to control in the steelmaking process and have better machinability than resulfurized or calcium-treated resulfurized steels. In this paper, the machinability of these steels has been investigated.

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2. Materials and Procedures

2.1 *Materials*

The experimental materials were melted in a middle-frequency induction furnace. The weight of each ingot was 50 kg. The chemical compositions of S-Ca, S-Ca-RE, S, and S-RE free-cutting steels are given in Table 1.

It can be seen from Table 1 that the chemical compositions, except for the amounts of calcium and rare earths, are close enough to be regarded as similar. Thus, we may consider that there are no differences in the matrix properties of these steels so long as they are processed under similar condition.

The ingots were hot rolled into bar 70 mm in diameter and 350 mm in length. These samples were heat treated at 875 °C for 3 h and then oil quenched. The hardness of the quenched samples was adjusted within 33 to 35 HRC through tempering. Finally, the samples, 68 mm in diameter and 330 mm in length, were obtained after being skinned off.

2.2 *Procedure*

A lathe with a variable spindle speed capability was used for turning tests. A microscope, precision of 0.01 mm, was used to measure the flank wear of high-speed steel (HSS) tools. In order to observe and measure the tip, flank, rake wear, and protective layer of P30 carbide, scanning electron microscopy (SEM) was used.

After turning, specimens of 12 × 12 × 14 mm were cut from the samples for quantitative analysis (automatic optical image analysis system) and energy dispersive system analysis of inclusions.

Table 1 The chemical compositions of the steels (wt %)

Steel	C	Si	Mn	S	P	Mo	Cr	V	Als(a)	O	N	Ca	RE
A	0.40	0.19	1.45	0.10	0.029	0.22	1.37	0.12	0.011	0.0055	0.0050	0.0030	...
B	0.40	0.20	1.43	0.10	0.028	0.22	1.37	0.12	0.020	0.0050	0.0050	0.0023	0.027
C	0.39	0.19	1.55	0.10	0.028	0.18	1.40	0.10	0.005	0.0060	0.0050	...	...
D	0.39	0.21	1.50	0.10	0.029	0.18	1.40	0.10	0.013	0.0050	0.0050	...	0.050

(a) Als, acid soluble aluminum

The tool geometry can be seen in Fig. 1:

- T_1 HSS tool (used in $v \leq 35$ m/min). $\gamma_0 = 10°$, $\alpha_0 = 8°$, $\alpha'_0 = 6°$, $\lambda_s = 0°$, $K_\gamma = 90°$, $K'_\gamma = 10°$.
- P30 carbide (used in $v \geq 120$ m/min). $\gamma_0 = -10°$, $\alpha_0 = 8°$, $\alpha'_0 = 6°$, $\lambda_s = -6°$, $K_\gamma = 75°$, $K'_\gamma = 14°$.
- Low cutting speed ($v \leq 35$ m/min): depth of cut $d = 1.5$ mm, feed $f = 0.1$ mm/rev, total cutting time $t = 240$ min.
- High cutting speed ($v \geq 120$ m/min): $d = 1.0$ mm, $f = 0.1$ mm/rev, $t = 20$ min.
- Dry cutting

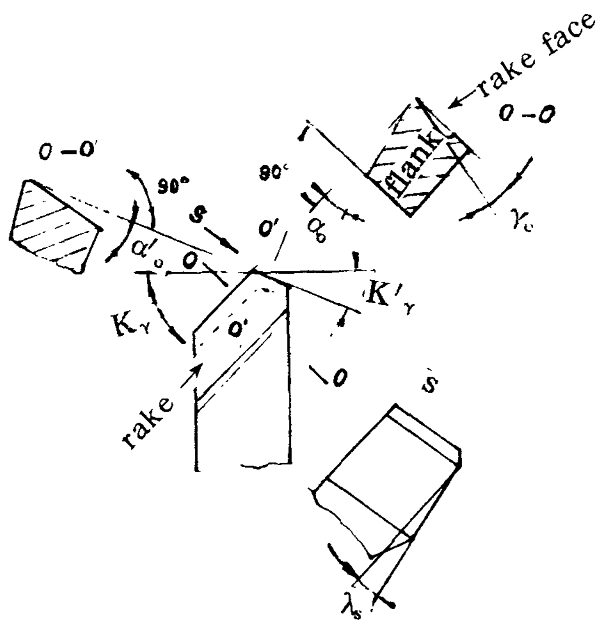

Fig. 1 Geometry terms of cutting tools

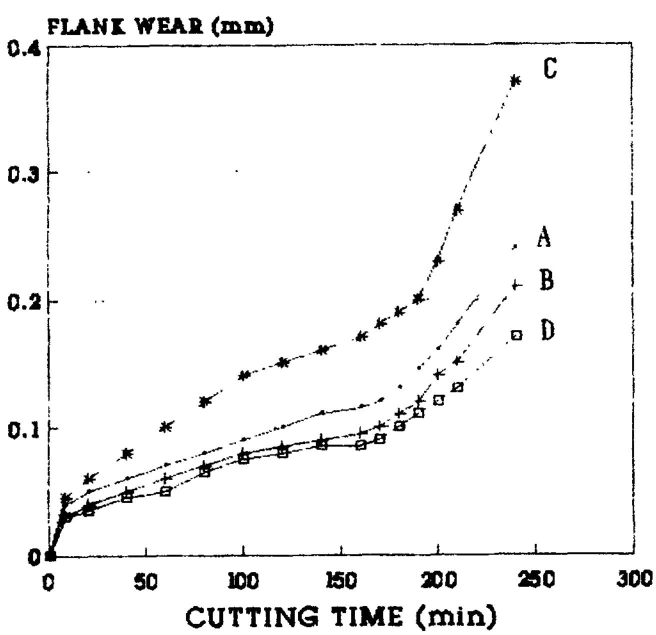

Fig. 2 Flank wear curves for type T_1 HSS cutting tools

3. Results and Discussion

3.1 *Analyses of the Inclusion Compositions, Shape, Size and Area Fraction in Experimental Steels*

Electro-probe microanalysis (EPMA) and image analyses were employed to determine the composition, shape, size, and area fraction of the inclusions. The results are given in Table 2.

3.2 *The Flank Wear of T_1 HSS Tools*

Machining tests of the four steels were carried out at the following cutting speeds: at 5 m/min for 80 min, then at 10 m/min for 40 min and 15 m/min for 40 min, and then at 20, 25, 30, and 35 m/min for 20 min, respectively. The total cutting time was 240 min. The total flank wear curves for T_1 tools are shown in Fig. 2. In the cutting speed range, wear on the flank of the tool was the dominant failure mechanism, not rake face wear due to the formation of built-up edges on the rake face.

Figure 2 shows that the highest degree of wear is for steel C. This may be attributed to the effect of inclusion shape on the maximum stress concentration (Ref 5):

$$\sigma_{max} = \sigma(1 + 2B/L)$$

where B and L are the width and length of the inclusion, respectively.

The expression shows that, the higher the ratio B/L, the higher the stress concentration, which leads to improved chip breakage, and thus reduced tool wear. Therefore it is not difficult to explain why steel A exhibits better machinability than steel C, and so do steels B and D, for their differences lie in the B/L ratio.

3.3 *The Wear of Cemented Carbide Tool (P30)*

Four steels were machined at 120 and 160 m/min. Catastrophic failure of the tools took place in several seconds when machining steel C, so the machining process for steel C was stopped. Cutting of the other steels was carried out smoothly. In the high cutting speed range, however, rake wear was the main factor affecting the tool life, for the flank wear was relatively smaller (as seen in Fig. 3), which agrees with an earlier study (Ref 6). SEM images of rake wear morphologies are presented in Fig. 3.

As can be seen from Fig. 3, the tools exhibited the maximum abrasive wear when machining steel D (Fig. 3d), followed by steel A (Fig. 3c), the minimum wear was exhibited when machining steel B (Fig. 3a). There was a protective layer (white layer) about 10 μm in thickness on the rake face of the tool when machining steel B (Fig. 3b), but no protective layer was detected on the rake face when machining steels A and D under the same conditions. The same conclusion was obtained at the cutting speed of 160 m/min. Steel B can form a protective layer on the rake face in the cutting speed range of 120 to 160 m/min, but steels A and D could not. Tools applied to machining steel D also exhibited noticeable crater wear (shown in Fig. 3d) caused by diffusion (Ref 8). Quantitative analysis of the protective layer was carried out by EPMA. The results are illustrated in Fig. 4 and Table 3.

According to Fig. 4 and Table 3, the protective layer contains 21.3 wt% of (Ce, La, Ca, Mn, S) and a slight amount of Cr and Fe, but little Al, Si, or O. The elements in the P30 tool (W, C, Co, Ti) were detected due to the thinness of the layer. The composition of the layer was related to the inclusions (Ref 3) of $(RE,Ca)_2S_3$-(Mn, Ca)S, defined as a eutectic and shown in Fig. 5, and (Mn, Ca)S. This composition differs from the compositions of the protective layers in calcium-containing free-cutting steel (Ref 6) and 20CrRES steel (Ref 7). Additionally, steel B presented better machinability than steels A and D in the cutting speed range of 120 to 160 m/min, because the protective layer on the rake face is supposed to prevent diffusion wear (Ref 8).

In the above cutting speed tests, the favorable effect of the inclusion shape on the machinability of steel D in the low cutting speed range disappeared when the cutting speed increased from 120 to 160 m/min. At the higher speed, the cutting properties of steels are more sensitive to the composition of the inclusions, because the cutting temperature increases with increase in the speed, which reduces the plastic differences between the inclusions and the matrix in the chip. Thus, the stress concentration on the inclusions-matrix interface would be reduced no-

Table 2 Analyses of the inclusion compositions, shape, size, and area fraction in experimental steels

Steels	A	B		C	D	
inclusion	(Mn,Ca)S	MnS	$(RE,Ca)_2S_3$-(Mn,Ca)S	MnS	MnS	RE_2S_3-MnS
Shape, λ	3.17	3.3	2.05	3.83	2.64	2.2
Length, μm	7.43	7.14	4.50	7.81	5.81	4.75
Fraction, %	0.524	0.43	0.159	0.56	0.38	0.156

Note: $(RE,Ca)_2S_3$-(Mn,Ca)S and RE_2S_3-MnS are both defined as eutectic. λ is defined as a shape factor ($\lambda = L/B$), where L and B are the length and width of inclusions.

Table 3 Quantitative analysis of the protective layer by EPMA

Parameter	Protective layer										Matrix
Element	Ca	Ce	La	Mn	S	Al	Si	O	Cr	Fe	W, C, Co, Ti
wt%	4.4	7.9	0.4	3.1	4.8	0.03	0.006	0.001	0.5	0.8	79.6

Table 4 The mechanical properties of the steels

	Longitudinal tensile test				
	MPa		%		
Steels	σ_b	σ_s	δ	ψ	a_{KT}/a_{KL}
A average	1201	1152	9.7	43.0	0.24
A variation, %	−3 to +4.5	−2.7 to +4.1	−2.0 to +3.2	−2.2 to +2.0	−7.3 to +3.5
B average	1218	1147	10.1	43.6	0.39
B variation, %	−4.0 to +4.1	−1 to +3.3	−1.0 to +2.3	−3.1 to +3.0	−6.4 to +2.9
C average	1192	1122	9.5	41.9	0.16
C variation, %	−3.8 to +5.0	−2.0 to +3.5	−1.1 to +2.0	−2.8 to +3.2	−6.7 to +3.1
D average	1177	1106	9.5	42.7	0.40
D variation, %	−3.6 to +4.3	−2.6 to +3.0	−1.5 to +2.4	−3.0 to +3.1	−6.3 to +4.0

Note: The hardness of the tested samples of the four steels were within 33 to 35 HRC under similar temper. a_{KT} and a_{KL} are transverse and longitudinal toughness (J/mm^2), respectively. σ_s is yield strength, σ_b is tensile strength, δ is elongation, and ψ is reduction of area. Five samples of each steel were used for the tensile test.

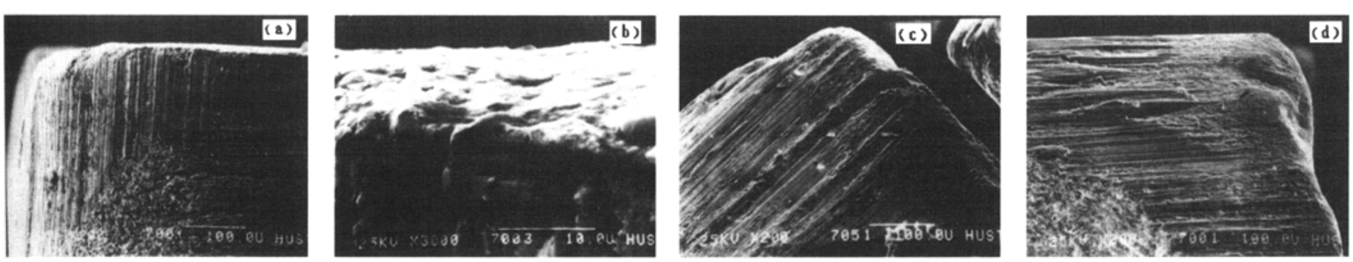

Fig. 3 SEM images of wear morphologies of P30 tools. (a) Tool used for cutting steel B. (b) Enlarged SEM image of the marked protective layer in (a). (c) Tool used for cutting steel A. (d) Tool used for cutting steel D

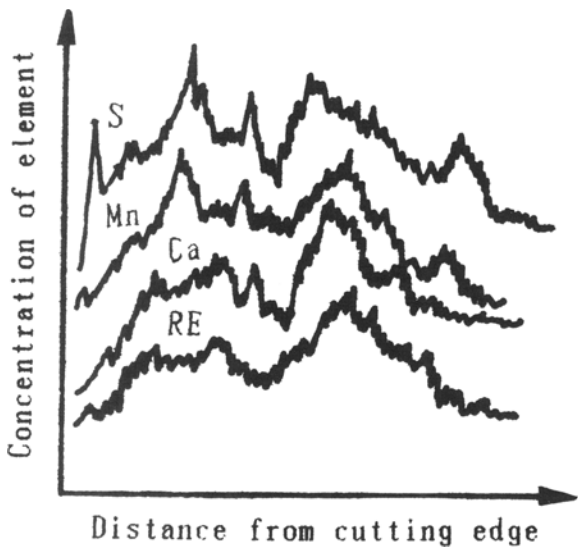

Fig. 4 The result of a line analysis of the rake face of a P30 tool used for cutting steel B by EPMA

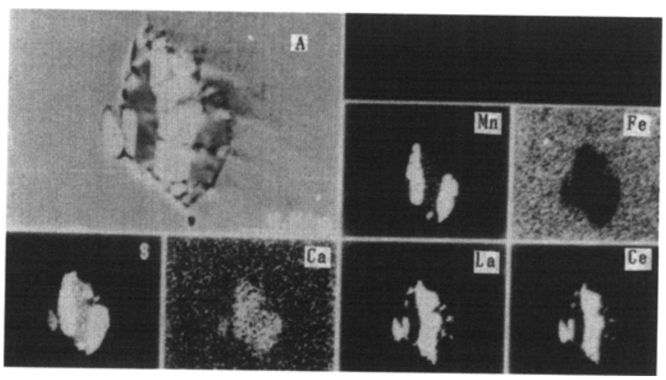

Fig. 5 EPMA images of eutectic in steel B (S-RE-Ca). A is a secondary electron image; the others are element mappings.

ticeably, and the chip breakage ratio would be remarkably lower than that at a lower cutting speed.

4. Mechanical Properties of Steels

The mechanical properties of the four steels are presented in Table 4.

It is shown in Table 4 that there were few differences among the longitudinal properties of the four steels but bigger difference in transverse section (e.g., the rate of Charpy impact toughness, (a_{KT}/a_{KL}). RE-treated or (RE + Ca)-treated steel has higher transverse toughness than only calcium-treated or only resulfurized steel.

5. Conclusions

- In low (≤35 m/min) cutting speed range, the higher the *B/L* ratio, the more favorable the machinability. Thus S-RE free-cutting steel has better machinability than only resulfurized steel.
- At high cutting speeds of 120 to 160 m/min, the cutting properties of steels are more sensitive to the composition difference of inclusions. S-RE-Ca free-cutting steel exhibited better machinability than S-Ca and S-RE free-cutting steels, because it can form a protective layer on the rake face of a P30 tool.
- There are few differences among the longitudinal properties of the four steels, but larger differences in transverse properties (such as Charpy impact toughness).

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References

1. J. Backman, "Calcium Injection Treatment of Steels from the User Point of View," paper presented at Scan-Inject III, 15-17 June 1983, Luea
2. C.A. Apple, The Relationship between Inclusion and the Machinability of Steel Processings, *Proc. 31st Mechanical Working and Steel,* Iron and Steel Society, 1989, p 381
3. L. Jiang, "The Role of Ca and RE in Modifying the Free-cutting Phase in Sulfur System Free-cutting Steel," Ph.D. dissertation, Huazhong University of Science and Technology, 1990
4. X. Wu, "Study on the Microstructure and Properties of Nonhardening and Tempering Plastic Die Steels," Ph.D. dissertation, Huazhong University of Science and Technology, 1995
5. J. Xiao, *The Toughness and Toughening of Metals,* Shanghai Science and Technology Press, 1982
6. S. Cengru, Z. Dong, et al., Investigation II: The Layer Adhering to Tool Face as Formed in Machining Ca-S Free-cutting Stainless Steel, *J. Northeast Univ. Technol.,* No. 3, 1993, p 285
7. X. Zhai and Y. Liu, The Application of Rare Earths in the Low Alloyed Steel: Research on the 20CrRES, *J. Northeast Univ. Technol.,* No. 1, 1982, p 65
8. X. Zhai and Y. Liu, The Application of Rare Earths in the Low Alloyed Steel: Research on the 20CrRES, *J. Northeast Univ. Technol.,* No. 1, 1982, p 68