Behavior of Oxide-layer Adhered on Tool Surface when Machining Ca-Deoxidized Steel

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Machining of Ca-Si deoxidized, Fe-Si deoxidized and conventionally deoxidized steels was investigated in order to reveal the effect and mechanism of the tool surface layer consistnig of oxides and sulfides in preventing tool wear. The tool surface layers were surveyed by the electron probe X-ray micro-analyzer, and the structural components of the layer were identified in this study.

The following concludions were obtained: When machining Ca-Si deoxidized or Fe-Si deoxidized steels, the oxides and sulfides form layers on the tool surface, which avoid the direct contact of the work iron with the tool carbides, prevent the diffusion of the tool material.

When cutting Ca-Si deoxidized steels, a semitransparent layer forms preferably on carbide tools which contain TiC, and it consists of 2 to 3 $CaO \cdot Al_2O_3 \cdot SiO_2$. In the case of Fe-Si deoxidized steels, an ashy-grey coloured layer forms preferably on ceramic tools and it consists of CaO, Al_2O_3, SiO_2 and MnS.

1. Introduction

When machining carbon steels manufactured for an identical specification, namely the same chemical composition and physical properties, the useful life of the cutting tool is often found different in the production batches. According to the latest results of cutting experiments conducted on various steels[2~4], this phenomenon relates largely to the adhesion to the tool surface of the included elements in the steels, especially those made by deoxidation.

This investigation aims to reveal the effect and mechanism of the tool-surface layer in preventing the tool wear when machining Ca-Si deosidized, Fe-Si deoxidized and conventionally deoxidized steels. Furthermore, the change of the adhesion of the tool-surface layer on various tool materials and its effect on the tool wear

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are investigated, and the composition of the tool-surface layers are estimated from the quantitative analysis of the layers.

2. Study on the Effect of the Tool Adhered Layer on the Tool Life

2-1 Experimental Procedure

Turning tests were conducted on an Okuma LS High Speed Lathe featured with a continuous cutting speed control. Cutting speed was measured by a digital counter which detected the rotation of a roller in direct contact to the work surface within the maximum reror of ± 3 m/min.

A clamp-on type tool holder and triangular expendable inserts of carbide tool P20 were employed. Tool geometry was—6° : end and side rake angles, 6° : end and side clearance angles, 30° : end cutting edge angle, 0° : side cutting edge angle, 0.5mm : nose radius. Work materials tested were cylindrical billets of carbon steels S 45 C, manufactured by convertors using conventional deoxidation (mark A-2), Ca-Si deoxidation (Ca-1) and Fe-Si deoxidation (F-1). The chemical composition of the test materials are shown in Table 1.

Table 1. Chemical composition of work materials.

Work Material	Chemical Composition (%)								
	C	Si	Mn	P	S	Cu	Ni	Cr	Ca
Conv. Deoxyd. A-2	.45	.28	.74	.010	.018	.10	.02	.12	—
Ca-Si Deoxyd. Ca-1	.45	.35	.72	.014	.011	.15	.07	.15	.0045
Fe-Si Deoxyd. F-1	.46	.25	.69	.019	.013	.18	.07	.12	.0001

Tests were run dry under the following conditions:

Depth of cut : 2.0 mm
Feed : 0.25 mm/rev
Cutting speed: 75 to 300 m/min

The tool life was limited in this experiment when the flank wear land (V_B) reached 0.2 mm or when the maxiumm crater depth (K_T) reached 0.03 mm. Interrupting the cutting operation at predetermined times, the tool flank wear was measured with a Nikon Toolmaker's microscope and the crater depth was measured with an optical sectioning micrometer until the tool wear reached the above limit.

After the tool-life test was over, the worn part of the tool surface was observed by an optical microscope and an electron probe X-ray micro-analyzer (E P M A). E M P A was used under the following condition:

Acceleration voltage : 20 to 30 KV
Current of the probe: 0.1 to 0.3 μA
Beam diameter : 1 to 2 μM

When quantitative information on the density of the tested element was to be obtained, the recorded data were compensated by the Birks' method for correction by the absroption, fluorescence and atomic number of the element.

2-2 Test Resutls

At various cutting speeds, the life of the tool used on the three test materialswas obtained as shown in Fig. 1 on bilogarithmic paper. Compared with the conventionally deoxidized steel A-2, the line of the tool which cut the Fe-Si deoxidized or Ca-Si deoxidized steels is largely prolonged. This tendency is obvious at the cutting speed below 210 m/min, where a decrease of cutting speed results in more emphasis on the difference in the tool life.

The distribution and density of the elements which adhered to the worn part of the tool surface are shown in Fig. 2. Fig. 2(a) is the distribution of Ca, Al and Si on the crater wear surface. Those elements form a layer adhered to the trailing half region of the chip-tool contact area on the tools which have cut the Ca-1 material. The adhered layer presu-

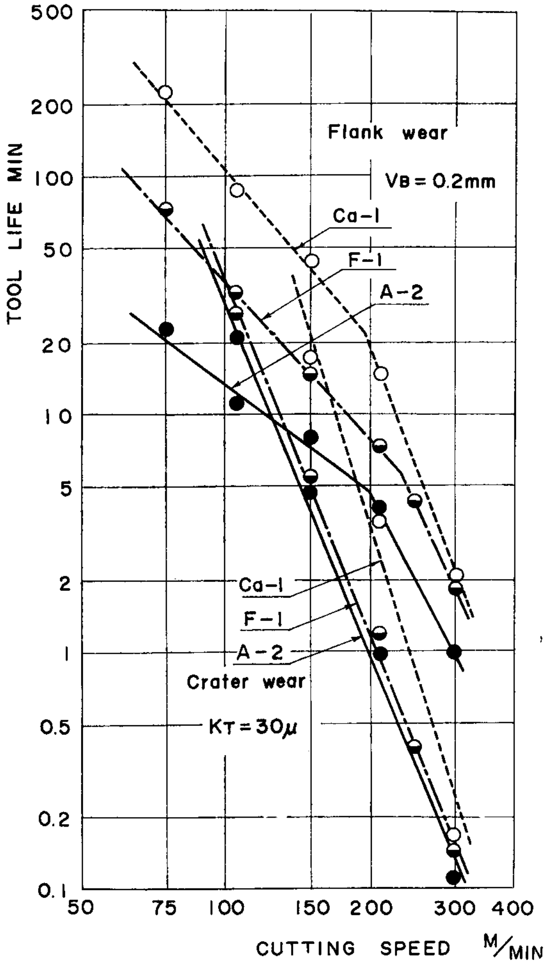


Fig. 1 Belation between cutting speed and tool life.
Tool: Carbide P 20, Depth of cut: 2.0 mm,
Feed: 0.25 mm/rev.

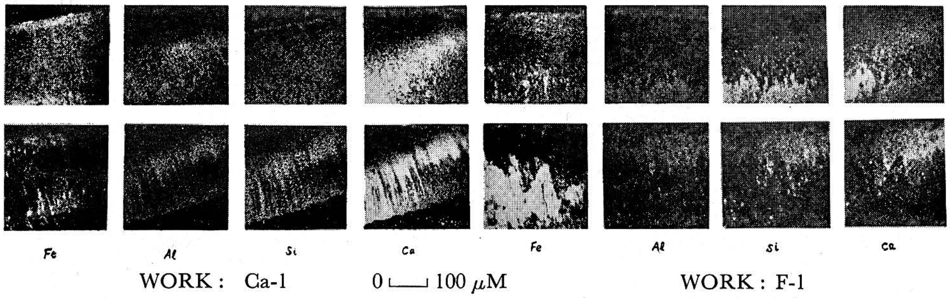
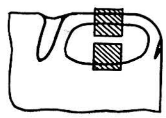


Fig. 2(a) Distribution of adhered material on the tool rake face.

Cutting speed: 150 m/min, Depth of cut: 2.0 mm
Feed: 0.25 mm/rev, Tool: Carbide P 20,
Cutting time: 60 min, EPMA: 30 KV; 0.2 μA.



mably consists of some of the non-metallic inclusions which have been contained in the work steels. Referring to the study by Opitz[4] and others, the ingredients of the layers are oxisde (CaO, Al_2O_3, SiO_2) and the sulfide (MnS).

On the tools used to cut the F-1 steel, Ca, Al, Si and Mn are also detected on the rake face. But in this case, the melitng point of the adhered material seems to be lower than the melting point of the material adhered in machining Ca-1 steel, since the adhered layer is pushed away from the chip-tool contact area when the cutting speed is 150 m/min and above. Considering these facts, the tool-life curve of Fig. 1 is interpreted to indicate that the adhered layre prevents the tool wear effectively even when the layer is very thin or softened and melted to some extent.

Fig. 2(b) shows the distribution of the density of the elements which is measured along a line vertical to the side cutting edge in the tool rake face. As seen from the figure, when machining the F-1 steel, Ca, Al, Si and Mh are altogether deposited at roughly identical positions on the tool. In case of the Ca-1 steel, Ca, Al and Si are deposited at identical positions, but only Mn in front of these elements. Adhered layers produced in cutting Ca-1 steel is richer in Ca and Al, but less in Si, Mn and Fe than those produced in cutting F-1.

On the flank wear surface of the tool, Ca, Al, Si, Mn and Fe are also detected as shown in Fig. 2(c). Since the flank wear surface is rougher than the crater wear surface, there are many grooves, along which those elements are deposited. Considering the result of tool life tests shown in Fig. 1, it becomes apparent that even under these conditions the adhered material is similarly effective inpreventing the flank wear.

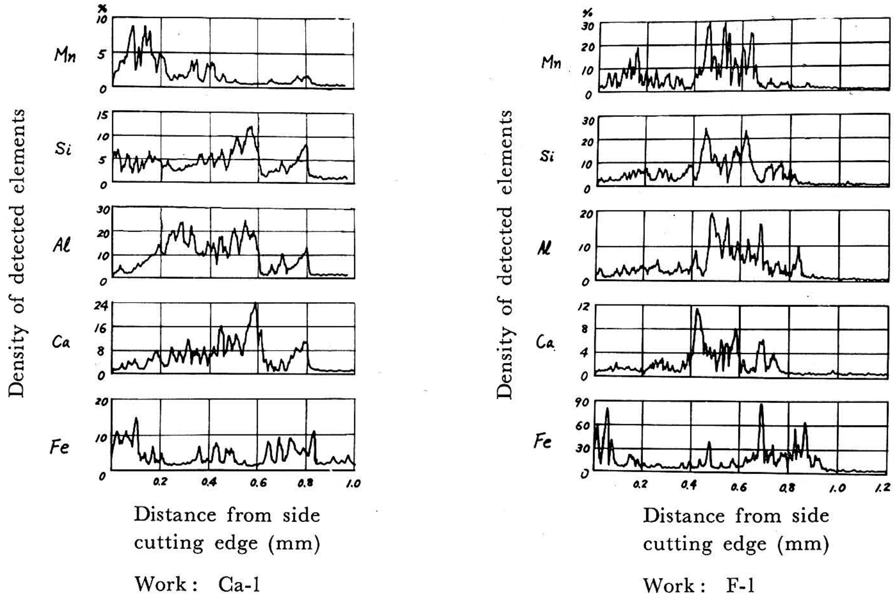
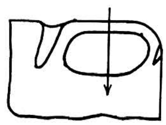


Fig. 2(b) Density distribution of adhered material on the tool rake face.

Cutting speed: 105 m/min, Depth of cut: 2.0 mm,
Feed: 0.25 mm/rev, Tool: Carbide P 20,
EPMA: 30 KV; 0.2 μA.



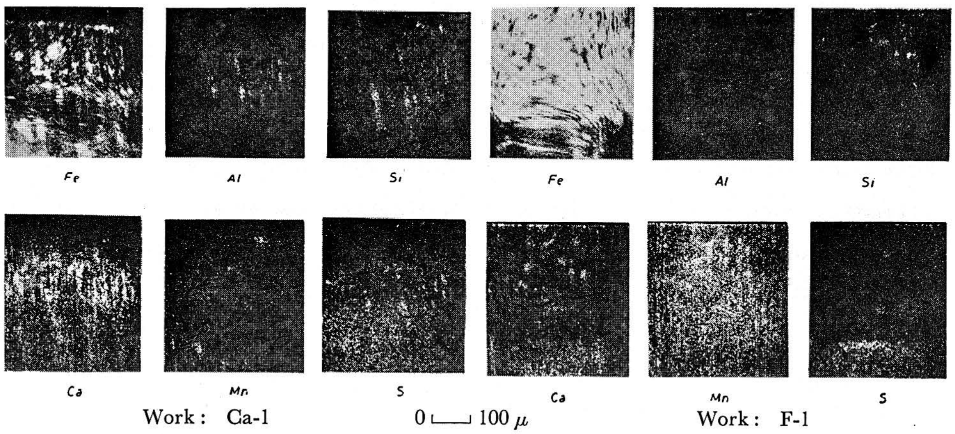
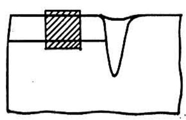


Fig. 2(c) Distribution of adhered material on tool flank surface.

Cutting speed: 150 m/min, Depth of cut: 2.0 mm,
Feed: 0.25 mm/rev, Tool: Carbide P 20,
Cutting time: 60 min, EPMA: 30 KV; 0.2 μA.



2–3 Consideration of the Action of the Layer Adhered on the Tool Surface

From the experimental results mentioned in the above, it is to be said that the layer of material which is deposited on the tool surface in machining specially deoxidized steels such as Ca-Si deoxidized and Fe-Si deoxidized steels, prevents the direct adhesion of iron to the tool surface. In this experiment, the adhered layer has the thickness of a few micrometers, over which the removed chip flows so that the temperature of the tool surface decreases due to the lubricating action of the layer and this reduces the rate of the diffusion of the tool material into the removed chip. Besides, even if the atoms still diffuse out of the tool material, it is difficult for the tool material to pass through the oxide film. This theroy which assumes the film as a diffusion barrier gives good explanations to the fact that the tool wear is prevented effectively when the layre is very thin and Fe adheres to the layer.

When the temperature of the adhered layre goes above a certain level by an inclease of the cutting speed, the adhered layer starts to soften or melt and flows away behind the tool-chip contact zone, thus the effect of the layer is lost. In the present study, this phenomenin seemingly occurred above the cutting speed of 210 m/min, and this supports the proposition that there is a certin range of cutting conditions for the layer to act effectively as pointed out by W. Konig[4)].

3. Formation of Adhered Lzayer on Various Tool Materials and Composition of the Layers

3–1 Experimental Procedure

The experiment was performed with the same equipment and work material as in section 2–1. Four kinds of tool material: carbide tool K 10 and P 10, cermet tool and ceramic tool, were used. All tools were used with a standard geometry of -5°: end and side rake angles, 5°: end and sie clearance angles, 15°: end and side cutting edge angles, 0.8 mm : nose radius.

Turning tests were undertaken without cutting fluid under the following conditions:

Depth of cut : 1.5 mm
Feed : 0.28 mm/rev
Cutting speed : 105, 150 and 210 m/min
Cutting length: 1050 meter per tool

After the test, the tool wear and the quality of the adhered material was examined: also, the quantitative analysis by E P M A was aplied on local areas of the adhered layer in order to estimate the composition of the layer from the weight percents of the existed elements.

3-2 Test Results

When machining the three test materials, the crater and flank wears of each tool proceeded as shown in Fig. 3. Both rake face and flank of carbide P 10 tool wore most rapid in machinig A-2 steel, followed by F-1 and Ca-1 steel in that order. A similar tendency holds with the flank wear of the cermet rool, although the crater wear was much smaller than that of P 10. Carbide K 10 tool indicated the most severe wear both on the rake face and the flank, the rate of which was, however, not connected with the work steel. On the contraty, the wear of the ceramic tool was least when cutting F-1 followed by Ca-1 and A-2, and this tendency was different from that of carbide P 10 or cermet tool.

This difference of tool wear rate among the work steels is closely related with the quantity of the adhered material over the tool surface. As shown in Fig. 4, the adhered layer formed in cutting Ca-1 steel covered more area of the surface of the carbide P 10 and cermet tools than that formed in cutting F-1 steed. In contrast to this the surface of the ceramic tool was covered by the adhered layer more in cutting F-1 steel than in cutting Ca-1 steel. With carbide K 10 tool, such a layer was not generated and only Fe adhered on the tool surface. The distribution of the element shown in Fig. 4 represents those around the tool rake face adhered

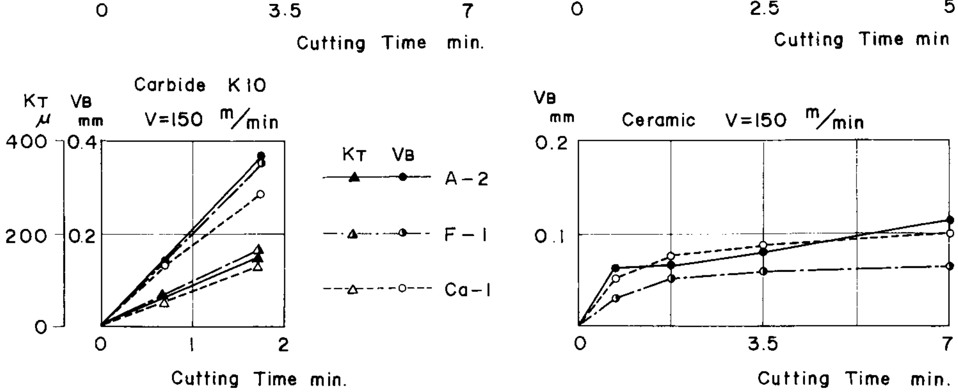


Fig. 3 Wear process of each tool
Depth of cut: 1.5 mm, Feed: 0.28 mm/rev, Cutting length: 1050 m.

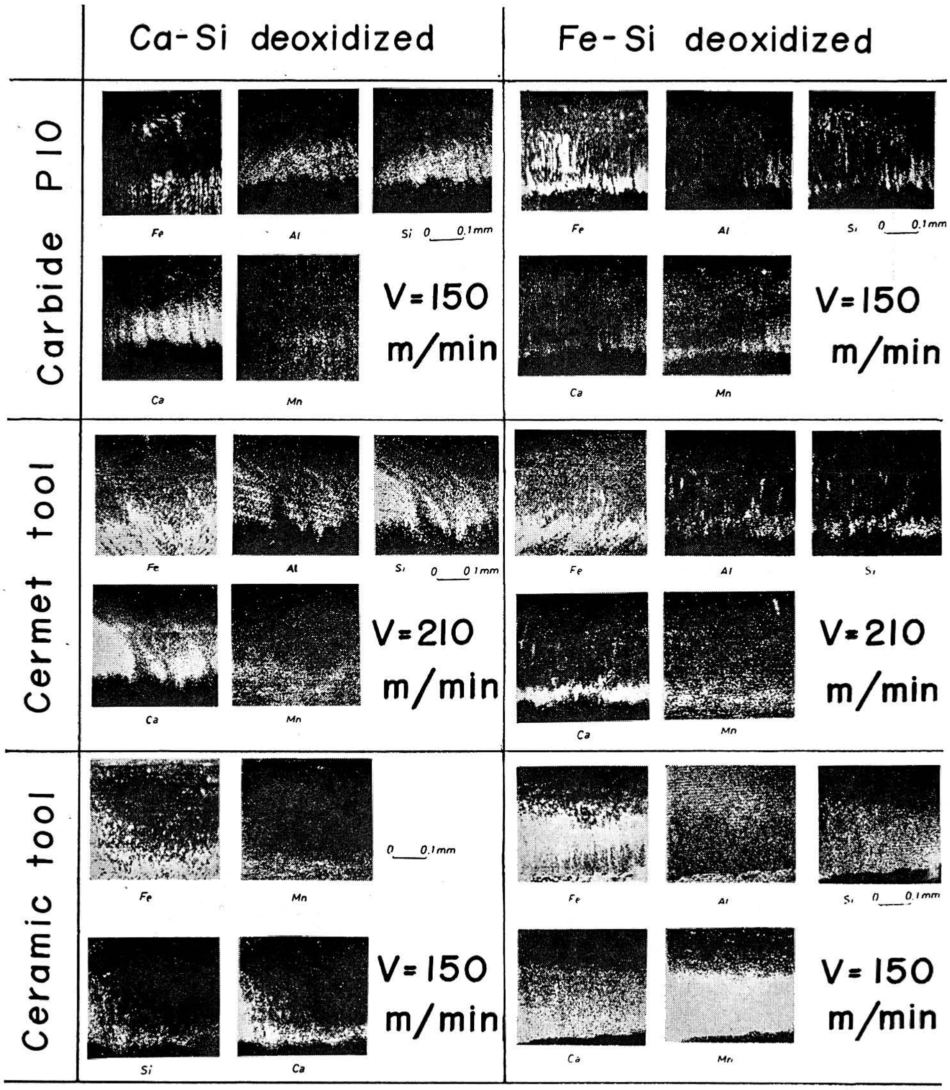
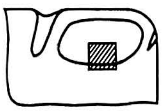


Fig. 4 Generation of tool surface layer on various tool materials.

Depth of cut: 1.5 mm, Feed: 0.28 mm/rev,
Cutting length: 1050 m.



material, whereas a similar tendency is observed on the tool flank.

The amount of the adhered layer, of which the thickness was as thin as 4 micrometers and below in the present study, should be investigated with the knowledge of the composition of the layer and the tool materials. For this purpose, the weight

Table 2. Chemical composition of the adhered layer on the tool rake-face.

a) Work : Ca-1, Depth of cut : 1.5 mm,
Feed : 0.28 mm/rev, Cutting length : 1050 m,
Compensated dy Birks' method

Tool Material	Cutting Speed (m/min)	Chemical Composition (%)		
		CaO	Al_2O_3	SiO_2
Cermet tool	105	45.4	30.3	24.3
	150	33.9	36.2	29.9
	210	38.1	45.7	16.2
Carbide tool P10	150	45.3	31.6	23.1
	210	43.3	35.8	20.9

b) Work : F-1, Depth of Cut : 1.5 mm
Feed : 0.28 mm/rev, Cutting length : 1050 m
Without Compensation

	Chemical Composition (%)			
	CaO	Al_2O_3	SiO_2	MnS
Cermet tool 150 m/min	12	27	32	29

ratio of the layer material was calculated based on the result of E P M A data. For the Ca-1 steel, Tab. 2(a) shows that the tool surface layer mainly consists of 2 to $3 \cdot CaO \cdot Al_2O_3 \cdot SiO_2$, the quantity of CaO and SiO_2 decreasing relative to that of Al_2O_3, as the cutting speed is raised. In case of machining the F-1 work steel, the composition of the formed layer was not uniform and varied at each point analyzed, among which a typical result is shown in Tab. 2(b). From this table it is found that the layer which is generated in cutting F-1 steel containes a comparatively large amount of MnS besides the aboe mentioned three oxides.

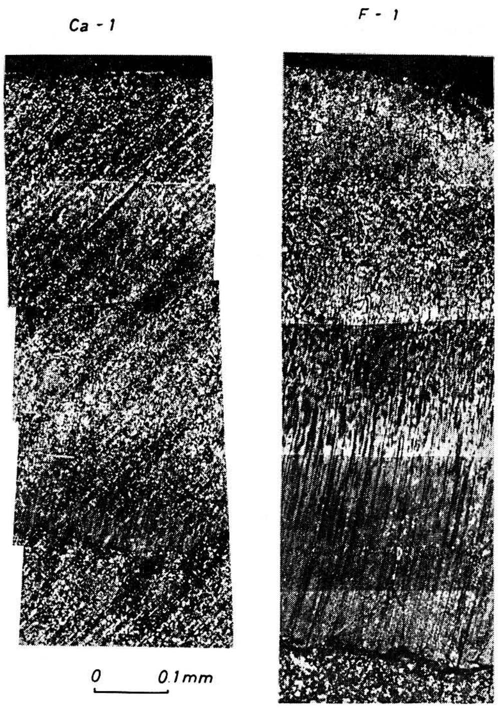
Examples of the optical microscope view of the layers are shown in Fig. 5. In those photographs, a semitransparent layer appeas adhered to the tool used for cutting Ca-1 steel, while an ashy-grey layer appears on that used for cutting F-1 steel, both formed on the last half of the tool-chip contact zone.

3–3 Interpretation on the Dependence of the Composition of the Layer on the Tool Materital

From the facts mentioned above, it is found that a semitransparent layer whose composition is around 2 to $3 \cdot CaO \cdot Al_2O_3 \cdot SiO_2$ is formd when machining Ca-Si deoxidized steel. It has been said that the formation of this layer depends on the Ti content in the tool[4], which, in this experiment, was ascertained by finding that the more the Ti content of the tool brings about the more adhered materials on the tool surface.

When machining Fe-Si deoxidized steels, an ashy-grey coloured layer formes preferably on ceramic tools and it onsists of CaO, Al_2O_3, SiO_2 and MnS. Comparing the results shown in Fig. 3 and Fig. 4, it is found that when the tool surface layer coveres the wider area, the more effectively it prevents tool wear irrespective of the kind and composition of the layer.

Furthermore the fact that the composition of the layer changes with the cutting condition as shown in Tab. 2, shows that the composition of the inclusions in work materials is not identical to that of the tool surface layer. It is inferred that various inclusions are molten together on he tool surfae by the high cutting temperature and pressure, and a layer is formed which has a new composition most suitable for the temperature and pressure existing at the interface.



Cermet tool Ceramic tool

Fig. 5 Photograph of tool surface layer taken by optical microscope.

Cutting speed: 150 m/min,
Depth of cut : 1.5 mm,
Feed : 0.28 mm/rev,
Cutting time : 7 min.

4 Conclusions

1) Machinability of the tested Ca-Si deoxidized and Fe-Si deoxidized steels was much beter from the view point o tool life compared with that of conventionally deoxidized steel. In this experiment the difference in tool life was greater in the low cutting speed range. The difference in tool life was caused by a tool surface adhered layer which was made from work inclusions and was effective to prevent tool wear by avoiding the direct contact of the work iron with the tool carbide

and preventing the diffusion of the tool materials.

2) When machining Ca-Si deoxidized steels, a semitransparent layer was generated on the tool surface, and it consisted of 2 to 3 $CaO \cdot Al_2O_3 \cdot SiO_2$ As cutting speed is increased, the CaO and SiO_2 content in the layer tends to decrease and that of Al_2O_3, increase.

3) When machining Fe-Si deoxidized stedels, the tool surface adhered layer had ashy-grey colour and consisted of CaO, Al_2O_3, SiO_2 and MnS.

4) Tool wear was decreased most effectively when the layer was thick and covered a broad area of tool surface. In this experiment the thickest and widest layer was generated when machining Ca-Si deoxidized steel by cermet tool, and Fe-Si deoxidized steel by ceramic tool.

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