Ground Surface Layer in α -Fe-Fe₃C alloys *

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This paper describes basic and systematic estimation for the residual stress, hardness and structure of the ground surface layer of α -Fe-Fe₃C alloys with volume fraction of cementites ranging from 1.0 to 14.1%. Furthermore, we also investigated the relation of the residual stress, hardness and structure in surface layer and grindability factors. The main results obtained are as follows;

- 1) The residual stress of Fe₃C phase in ground surface layer is measured by a trial-made X-ray strain meter.
- 2) The residual stress ratio in the two phases $\sigma_{ic}(\text{Fe}_3\text{C})/\sigma_{if}(\alpha\text{-Fe}) = 4 \sim 5$ is obtained in the case of 10% Fe₃C or more.
- 3) With an increase in the grain size of Fe₃C ($\bar{d}_0$) and Fe ($\bar{d}$) crystals, the fluctuating and depth values of residual stress distribution increase gradually. Furthermore, the residual stress of the lamellar cementite is larger as a whole when it is compared with that of the spheroidal cementite.

1. Introduction

The phase diagram of Fe-C system can be seen by rearranging it to a phase diagram of α -Fe-Fe₃C system. For instance, in the ground surface layer of a workpiece of this alloy system, the distributions of residual stresses, the distribution of hardnesses, and the change in structure are brought on by only the deformation of both α -Fe phase and Fe₃C phase. Therefore, some corresponding relation must exist between them. Heretofore, regarding the evaluation of ground surface layer, numerous studies have been carried out on α -Fe phase,⁽¹⁾⁽²⁾⁽³⁾ and the formation mechanism of ground surface layer from α -Fe phase has been almost clarified.⁽⁴⁾⁽⁵⁾ On the other hand, when the optimizing control of ground surface layer is aimed at in future, it seems that it will be necessary to show it concretely by relating to some criterion for the evaluation without fail, namely some criterion of the metal to be worked. As one attempt, the authors considered that the criterion of this study must be placed in the phase diagram of α -Fe-Fe₃C system when a workpiece is an Fe-C alloy, for instance. It means that if the grinding conditions are known beforehand, there may be the possibility to grasp the respective changes in the residual stress, hardness and structure of ground surface layer in some extent corresponding to each structure given in the phase diagram.

As it is said that studies of metals pursue the history of strengthening, the authors considered that there might be an aspect of being able to understand more easily the changes in the various factors of ground surface layer rather in the study through the Fe₃C phase with large effect on deformation. For example, the breaking stress of Fe₃C phase is several tens times greater than that of α -Fe phase. Grindability factors such as grinding force, grinding temperature, the surface roughness, and the structure of chips, change macroscopically with the synthesis of microscopic change owing to the grinding of the alloy structure with α -Fe and Fe₃C phases. On the other hand, when the fact that the macroscopic residual stress of ground surface layer occurring as the synthesis of α -Fe phase and Fe₃C phase structures can be simulated with the changes in grinding force and grinding temperature is considered,⁽⁴⁾ it is expected that some corresponding relation is found for the amount of Fe₃C between the various factors of ground surface layer including the hardness and structure and the various factors of grindability. In this way, if the results of individual macroscopic changes occurring synthetically are known and related to the grinding damage of workpieces, namely the residual stress, hardness and structure of ground surface layer, the industrial merits derived there from will be important because the grinding damage becomes predictable from the individual macroscopic changes. Also if the changes in the various factors of ground surface layer are grasped easily by knowing the changes in the structure and form of chips, more merits will arise in the practical aspect also.

Moreover, as a microscopic evaluation of ground surface layer, the present study realizes the measurement of the residual stress in Fe₃C phase of ground surface layer, then grasps the relation

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to α -Fe phase, and further, the relation to the crystal grain size of the parent phase α -Fe and the change of shape of Fe_3C particles, which are the important structures in α -Fe- Fe_3C phase diagram. Consequently, the residual stress in the ground surface layer of Fe-C alloy with annealed and normalized structure can be almost known. Moreover, similar thorough investigation is carried out on the various other factors of ground surface layer.

2. Experimental apparatus and method

Without grinding fluid, downward plunge grinding was carried out once with a grinding wheel of WA46mV at a peripheral speed of $V=1800\text{m/min}$, a work speed of $v=5\text{--}20\text{m/min}$, and depth of cut in the range $d=10\text{--}70\mu\text{m}$. The works were the same kinds of materials as those used previously⁽⁵⁾, and the same heat treatment was applied. Height of the works, grinding width and grinding length were 15, 15 and 50mm, respectively. The works were made of 8 kinds of steel with the volume fraction of Fe_3C ranging from 1.0 to 14.1%. However, considering that the works have a crystalline texture because of the rolled materials, sufficient diffusion heat treatment was carried out in a non-oxidizing furnace by holding them for 30min at $800\sim 950^\circ\text{C}$, 50°C above the A_3 transformation point. The residual stress in ground surface layer was determined by $2\theta\text{--}\sin^2\psi$ method using an X-ray stress measuring equipment of parallel beam type and a diffractometer mentioned later. Besides, the hardness of ground surface layer was measured with a microhardness tester (5gr minimum load), and the structure was observed with an electron microscope of JEM 7A type (100KV accelerating voltage) and a JXM 50A scanning electron microscope with an X-ray microanalyzer.

3. Trial-made equipment for measuring residual stress in Fe_3C phase.

The measurement of the residual stress in Fe_3C phase with the X-ray stress measuring equipment of parallel beam type described in Chapter 2 is impossible in principle. In short, the X-ray diffraction angle of Fe_3C phase is very low as compared with that of α -Fe phase. If the incident angle ψ of X-ray is taken low to the normal ON of a ground surface shown in Fig. 1 for example, the diffracted beam occurs as shown with the broken line in the figure in such case as ψ' . Such thing suggests that X-ray must be diffracted higher than a specimen surface. However, even in case of such $\sin^2\psi$ ($\psi=0^\circ, 15^\circ, 30^\circ$ and 45°) as that in Chapter 2 and Glocker method ($\psi=0^\circ$ and 45°), it is possible if the material with the diffraction plane of sufficiently large ψ X-ray intensity at the Bragg angle $\theta > \frac{\pi}{4} + \frac{\pi}{4}$ exists. When the changes in the X-ray diffraction intensity curves of α -Fe and Fe_3C phase were measured with a dif-

Fig. 1 Relation of the incident and diffraction angles of X-ray.

fraction intensity curves of α -Fe and Fe_3C phase were measured with a diffractometer, the record in Fig. 2 was obtained. From this record, in the selection of a diffraction grating plane (hkl), there is the theoretical background indicating that

Fig. 2 X-ray diffraction intensity curves of α -Fe and 11.3% Fe_3C alloys.

the measurement accuracy is improved as angle 2θ is high and the ratio I/I_1 of the X-ray diffraction intensity I shown in Table 1 and the highest intensity I_1 have high values.⁽⁶⁾

Table. 1 X-ray diffraction intensity of a diffraction grating plane (hkl).

dA	I/I_1	hkl
2.54	5	020
2.38	65	112, 021
2.26	25	200
2.20	25	120
2.10	60	121
2.06	70	210
2.02	60	022
2.01	100	103
1.97	55	211
1.87	30	113
1.85	40	122
1.76	16	212
1.68	15	004, 023
1.61	7	221
1.58	20	130

For example, in the equation derived by differentiating the Bragg equation and rearranging it, $1/\cot\theta_0$ has the role of amplifying lattice strain $\Delta d/d$, consequently the value of $1/\cot\theta_0$ increases by about ten times in low angle $\Delta\theta$ as compared with high angle $\Delta\theta$. Accordingly, the sensitivity of $\Delta\theta$ corresponding to $\Delta d/d$ becomes high. Moreover, considering the various facts affecting X-ray diffraction method, such that the error in the stress value corresponding to the statistical fluctuation of X-ray becomes smaller as I is larger,⁽⁷⁾ it was decided to grasp the correspondence of $\alpha\text{-Fe}$ (211) and Fe_3C (122) phases as for the residual stress in $\alpha\text{-Fe}$ and Fe_3C phases. For the measurement of the residual stress in both phases, it was decided to adopt the X-ray diffraction principle according to the reflection method by Schulz as the result of considering various method so that it is not necessary to take off samples and measurement can be carried out simply by a single set-up only. It will suffice to provide a supporting stand, on which a sample is placed at any position in the Rowland circle, to be rotatable around the normal to the sample surface on it and also around the horizontal axis. The X-ray total angle diffraction equipment manufactured for trial is so constructed that the X-ray from the point focus source diffracted on a sample surface can be counted with a scintillation counter. There are various methods to summarize X-ray diffraction intensity curves, but in the present study, the curves were obtained by using the results of both the counting by means of constant count and the counting

by means of constant time, and the curves were approximated with probability density function.⁽⁸⁾ Since the effective irradiation area of X-ray is 5mm^2 , the measured residual stress is regarded as the average of the phases existing in this area.

The calculated residual stress σ_ψ can be obtained from the Bragg equation and the theory of elasticity.

$$\sigma_\psi = K \frac{2\theta}{\sin^2\psi} \quad (1)$$

However, assuming that $K = \frac{E}{2(1+\nu)} \cot\theta$,

Young's modulus E_c (Fe_3C) = $21.6 \times 10^3 \text{kg/mm}^2$, E_f ($\alpha\text{-Fe}$) = $21 \times 10^3 \text{kg/mm}^2$, Poisson's ratio $\nu(\text{Fe}_3\text{C}) = 0.46$, $\nu(\alpha\text{-Fe}) = 0.30$, diffraction angle $\theta_0[\text{Fe}_3\text{C}(122)] = 38.23^\circ$, $\theta_0[\alpha\text{-Fe}(211)] = 78.04^\circ$,⁽⁸⁾⁽⁹⁾ $K = -161.1 \text{kg/mm}^2$ for $\text{Fe}_3\text{C}(122)$ and $K = -30.5 \text{kg/mm}^2$ for $\alpha\text{-Fe}$ were obtained. The method of determining σ_ψ by summarizing records and drawing $2\theta\text{-}\sin^2\psi$ graphs is described in detail in "X-ray Stress Measuring Method" (published by the Society of Materials Science, Japan) and by Hanabusa (on Fe_3C),⁽⁸⁾ therefore it is omitted here. Besides, there is some problem in the application of the equation (1) to the structure with intense anisotropy such as ground surface layer as Taira et al.⁽¹⁰⁾ mentioned on the structure of rolled materials, but the researchers in this field of X-ray stress measurement, it have not reached, such stage yet that a unified view can be disclosed, therefore it was expressed according to the conventional equation (1). The distribution of residual stresses in the depth direction from ground surface was measured successively after electrolytically polishing with the solution of acetic anhydride (9 volume rate) and perchloric acid (1 volume rate).

4. Estimation of residual stress in ground surface layer by means of Fe_3C phase

4.1 Residual stress in Fe_3C phase

The residual stresses σ_{RF} and σ_{RC} in $\alpha\text{-Fe}$ and Fe_3C phases measured with X-ray shown in Fig. 3 are those in grinding direction obtained by determining the distribution from ground surface toward depth direction by substituting respective values into the equation (1). The stress in Fe_3C phase showed a tensile stress of abnormally large value which has never been known in $\alpha\text{-Fe}$ phase so far.

As the amount of Fe_3C increases, abrasive grains turn out to grind relatively more Fe_3C phase which is ten times as hard as $\alpha\text{-Fe}$ phase, therefore they are apt to glide more, and simultaneously, it is considered that the plastic deformation negligible as compared with that of $\alpha\text{-Fe}$ takes place, accordingly it is known qualitatively that grinding temperature drops in some extent together unite a reduction of shearing heat and the like, and as increase of the amount of Fe_3C .⁽⁵⁾ On the basis of the established theory heretofore

Fig. 3 The stresses σ_{RC} and σ_{RF} in α -Fe and Fe_3C phases, and the macroscopic stress σ_M .

that the residual stress in ground surface layer is generated by thermal effect and mechanical effect, Kakino and Eda⁽⁴⁾ derived by simulation the residual stress distribution in the α -Fe phase of ground surface layer in the case of cutting and grinding. Moreover, they found out a rising of cutting and grinding temperatures causes a higher tensile residual stress, and that an increase of cutting and grinding forces causes a compressive residual stress. From these facts, the drop of grinding temperature due to the increase in the amount of Fe_3C is regarded as a cause of reducing the tensile stress in α -Fe phase. On the other hand, as increase in the mechanical strength of works due to a decrease in the grinding temperature causes an increase in the grinding force. Eventually, compressive residual stress is produced in α -Fe phase. Accordingly, the residual stress in the α -Fe phase of ground surface layer accompanying an increase in the amount of Fe_3C turns out to shift gradually to compression side. When the quality of works is evaluated from the fact that compressive residual stress takes place in α -Fe phase, the excellent material characteristics are provided in the presence of this stress regarding the wear resistance, fatigue strength and stress corrosion resistance.⁽⁵⁾ On the other hand, owing to abnormally large tensile stress in Fe_3C phase, it is emphasized, the aforementioned characteristics are deteriorated, and the Fe_3C

crystal grains more microscopic than α -Fe grains turn out to be the trigger and the nuclei to breaking. The main cause why such a high stress takes place in Fe_3C phase is owing to the fatal characteristics of the strengthening of Fe_3C grains in Fe-C group alloy. In short, the Fe-Fe bond in the crystalline structure of Fe_3C in Fig. 1 is a metallic bond, but the Fe-C bond involves the character of covalent bond, and the bonding strength of the latter seems to be about twice as high as that of the former. After all, as seen in Fig. 1, the atomic configuration in Fe_3C crystals is extremely complex as compared with that of ordinary metals, and a remarkable anisotropy is observed. Consequently, the breaking stress is several tens times as high as that of α -Fe and takes the value in the range 400-800 kg/mm² extending over a wide range. On the other hand, although the hardness, $H_v(Fe_3C)=1180-1250$, is about ten times as high as $H_v(\alpha-Fe)=120$, the dispersion of these values is small. Including such characteristics, it can be supposed that Fe_3C phase is remarkably brittle and its plastic deformation is very small as compared with α -Fe phase. The melting point of Fe_3C is 1212°C (1207°C according to some report) and is about 300°C lower than that of α -Fe (1540°C), but the decomposition into Fe and C atoms begins at about 500°C. However, in the range of this experiment, the decomposition of Fe_3C was not observed as the result of having examined the skin layer of ground surface positioned in the vicinity of ground point by the analysis with an X-ray microanalyzer and the observation with an electron microscope. This fact suggests that the basic physical and chemical properties of Fe_3C were little changed in the vicinity of ground point, and it seems appropriate to presume that various effects are exerted on the mechanism of forming ground surface layer with the characteristics close to those at normal temperature. Besides, if it is assumed that two phases form the composite structure on the whole, Fe_3C phase is regarded to have high sensitivity locally to the composite structure as it affects corresponding to the microscopic change, and it is considered that α -Fe phase makes a macroscopic change corresponding to the whole composite structure. The relation of residual stress in (1.0-14.1)% Fe_3C and α -Fe phases is determined, assuming that Fe_3C and α -Fe phases have the above described characteristics.

The stress σ_{RC} of Fe_3C phase and the stress σ_{RF} of α -Fe phase measured with X-ray are considered to be the superposed values of the macroscopic stress σ_M on sample surface and the microscopic residual stresses σ_{ic} , σ_{iF} of Fe_3C and α -Fe phases,⁽⁶⁾ accordingly resulting in

$$\sigma_{RC} = \sigma_M + \sigma_{ic} \quad (2)$$

$$\sigma_{RF} = \sigma_M + \sigma_{iF} \quad (3)$$

Also denoting the volume fraction of Fe_3C as q ,

$$q\sigma_{RC} + (1-q)\sigma_{RF} = \sigma_M \quad (4)$$

the equation for stress equilibrium is obtained.

For example, the distribution of σ_M in Fig. 3 is determined by substituting the stresses σ_{RC} and σ_{RF} measured with X-ray at 11.3% and 14.1% Fe_3C shown in the figure into the equation (4), calculating and plotting respective σ_M by using respective values obtained with depth below ground surface. Moreover, the distributions of σ_{ic} and σ_{if} in the figure are obtained by substituting these values into the equations (2) and (3), calculating σ_{ic} and σ_{if} similarly and rearranging them. Thus, determining the values of σ_{ic} and σ_{if} in the range of (1.0–14.1)% Fe_3C and comparing the distributions of respective residual stresses, the definite correspondence was observed in σ_{ic}/σ_{if} in some range. For example, as the amount of Fe_3C exceeds 10%, the relation of almost $|\sigma_{ic}/\sigma_{if}|=4\sim 5$ exists. At 11.3% Fe_3C , $|\sigma_{ic}/\sigma_{if}|=4.12$ and at 14.1% Fe_3C , $|\sigma_{ic}/\sigma_{if}|=4.34$ were obtained. However, as the amount of Fe_3C is reduced below 10%, the dispersion of σ_{ic} values increased, therefore the rearrangement was not able to be made easily as in the case of 11.3% and 14.1% Fe_3C in Fig. 3. As an example, in the case of 3.3% Fe_3C , the dispersion accounted to as 50~70% of the absolute value of σ_{ic} , and it became more conspicuous as the amount of Fe_3C was smaller. Thus, on the residual stress σ_{ic} in Fe_3C phase, the approximate value can be known in the range of Fe_3C amount where the equation $|\sigma_{ic}/\sigma_{if}|=4\sim 5$ holds, if the volume fraction q is known, by substituting σ_{RC} and σ_{RF} measured with X-ray into the equations (2), (3) and (4), and obtaining the relation $|\sigma_{ic}/\sigma_{if}|=4\sim 5$.

4.2 Shape and size of Fe_3C phase and diameter of crystal grains of α -Fe phase

As the method of relatively easily changing the shape and size of Fe_3C phase in a laboratory, the spheroidizing heat treatment of Fe_3C was carried out. Taking 11.3% Fe_3C as an example, it was heated for 1 hour at 870°C, oil quenched, and tempered at 700°C for tempering times of $t=1, 3, 5, 20, 50, 100$ and 200 hours, the mean diameters of Fe_3C grains, $\bar{d}_0=0.3, 0.43, 0.48, 0.8, 1.1, 1.5$ and $2.0 \mu m$ were obtained. These values were summarized with an equation of $\bar{d}_0=0.3t^{0.7}$. As for the distribution of residual stresses on α -Fe (211) of ground surface layer, the change of residual stress in depth direction (hereinafter, referred to as fluctuating value) is larger as $\bar{d}_0$ is larger, and shows the tendency of gradual reduction as $\bar{d}_0$ becomes smaller. However, it was not found that the residual stress took the values in a definite proportional relation to the diameter of Fe_3C grains and changed the distribution. Moreover, it is not possible that $\bar{d}_0$ coincides with same grain diameter for (1.0–14.1)% Fe_3C amount, but $\bar{d}=0.38 \mu m$ ($t=0.5hr$), $0.76 \mu m$ ($t=7hr$), and $1.30 \mu m$ ($t=35hr$) for 1.0%

Fe_3C , $\bar{d}_0=0.44 \mu m$ ($t=0.5hr$), $0.77 \mu m$ ($t=7hr$), and $1.42 \mu m$ ($t=35hr$) for 3.3% Fe_3C , $\bar{d}_0=0.49 \mu m$ ($t=0.5hr$), $0.78 \mu m$ ($t=7hr$), and $1.20 \mu m$ ($t=35hr$) for 7.4% Fe_3C were produced with the same heat treatment conditions as in the case of 11.3% Fe_3C , and the change in the residual stress σ_{RF} on ground surface was plotted in relation to Fe_3C amount and summarized. As the result, the residual stress on ground surface was smallest around 3.0% Fe_3C , and largest around (7.0–8.0)% Fe_3C . This change almost agrees with the tendency of the change in the amount of lamellar Fe_3C . Besides, the illustration including the physical meaning is not clear, but this change in relation to Fe_3C amount appears also in the changes of grinding force, surface roughness, and the plastic flow of ground surface layer. Accordingly it is recognized that the possibility of carrying out some quantitative treatment exists among the factors determining grindability. However, the amount of plastic flow was defined by the flow of pearlitic structure, which can be confirmed with an optical microscope of 1000 magnification, and expressed by measuring both the amount of flow (l_f) in grinding direction and the depth (d_f) till the flow is observed. Moreover, the residual stress when $\bar{d}_0$ was changed for respective amounts of Fe_3C showed the same tendency as in the case of 11.3% Fe_3C mentioned before.

Next, comparing spheroidized Fe_3C with lamellar one mentioned in the paragraph 4.1, for example as shown in Fig. 4, both the depth of distribution and the

Fig. 4 Comparing the residual stress in the case of spheroidizing with lamellar Fe_3C .

fluctuating value of residual stress (in grinding direction) are large in the case of lamellar Fe_3C . This trend was observed similarly in any amount of Fe_3C . Also in the residual stresses on spheroidized Fe_3C (122) and α -Fe (211), it was found similarly that the dispersion of σ_{ic}/σ_{if} values became gradually smaller and the relation of $|\sigma_{ic}/\sigma_{if}|=4\sim 5$ was obtained as Fe_3C increased beyond 10%, as shown in the case of lamellar Fe_3C . However, as pointed out by Taira,⁽¹⁰⁾ here it is necessary to consider the introduction of an equation in place of the equation (2), in which the predictable exerted on the residual stress

in ground surface layer, of the shape of secondary phase grains being made spheroidal or lamellar, and of a crystal texture more remarkable that rolled material being formed, in short to take into account the anisotropy, but actually, the treatment with the expression including it is not yet attained. Therefore, this comparison according to the shape is the result calculated persistently as an example following this experimental apparatus and the equations (2)~(4). Thus, as for the distribution of residual stresses in the two phase alloys of α -Fe and Fe_3C , the residual stress on the ground surface on α -Fe and Fe_3C phases can be almost known by referring to grinding conditions if the results obtained by knowing the shape and size of Fe_3C phase and the amount of Fe_3C are summarized beforehand. Also in the results of investigation including the distribution profile, a certain tendency was recognized, but the conclusion was refrained from in view of the reproducibility of data including the X-ray accuracy of actual machines and grinding experiments.

Next, as of the residual stress distribution when the diameter d of crystal grains of α -Fe parent phase was changed, the fluctuating value and the distribution depth of residual stress decrease as the grains become gradually smaller from $d=40\text{ }\mu\text{m}$ to $d=13.4\text{ }\mu\text{m}$ as in the example of Fig. 5. However in this measurement, various problems as feared arise in the accuracy of X-ray measurement as d becomes larger,⁽⁶⁾ but here, it may be considered the result of the experiment carried out following persistently such method. The fact that the distribution of residual stresses showed such tendency in relation to d change can be predicted from the result that grinding force and grinding temperature can be arranged according to the empirical formula by Holl-Petch. In short, the flow stress σ_f changes almost in proportion to $d^{1/2}$, accordingly for example, α -Fe phase becomes more ductile as d increases, and the depth of deformation and

Fig. 5 Distribution of residual stress due to crystal grain size (d) of α -Fe phase.

the amount of plastic flow of ground surface layer are increased unite it. Accordingly the amount of elastoplastic strain of ground surface layer increases as shown in Fig. 5, and the distribution depth and the fluctuating value of residual stress are deemed to increase as d becomes larger.

5. Relation between grindability and respective factors of ground surface layer

5.1 Hardness and structure of ground surface layer and grindability factors owing to the amount of Fe_3C

It was mentioned that in the range of 6.0~8.0% Fe_3C , the residual stress on ground surface took the largest value together with a series of grindability factors such as grinding force, grinding temperature, and the surface roughness, but the same thing can be said about the work-hardened layer (20 gr measurement load) as shown in Fig. 6. This measurement shows the mean value of 7 points measured at the

Fig. 6 Hardness in the work-hardened layer as a function of the amount of Fe_3C .

same depth. In 1.0~14.1% Fe_3C , for example, the work-hardened layer of 7.4% Fe_3C showed the highest hardness on the skin layer of ground surface, and α -Fe parent phase was hardened by about 45%, thus a value about 10~20% higher as compared with others was shown. Such increase in hardness was observed in chips (flow type, shear type, and tear type) as compared with workpieces (bulk) and reached the highest also at the same 7.4% Fe_3C . The exact proof is not obtained at present as to why the grindability and the quality of ground surface layer deteriorate in the range of (6.0-8.0)% Fe_3C and improve at about 3.0% Fe_3C . However, it is technologically valuable that the corresponding appearance of respective changes in works, chips, and grinding wheels was able to be

derived in some extent. Such relation appeared also in the change of ground surface of (1.0-14.1)% Fe_3C shown in Fig. 7. Namely, a ground surface of very smooth and with small plastic flow as compared

Work speed $v=5\text{m/min}$
Depth of cut $d=50\mu\text{m}$

Fig. 7 Ground surface in the range of 1.0~14.1% Fe_3C .

derived in some extent. Such relation appeared also in the change of ground surface of (1.0-14.1)% Fe_3C shown in Fig. 7. Namely, a ground surface of very smooth and with small plastic flow as compared with others was presented in the vicinity of 3.0% Fe_3C . On the contrary, a rough ground surface having less grinding streak due to micro-cutting edges as compared with others was presented at (6.0-8.0)% Fe_3C . Thereupon, in order to compare the intensity of this change, a peculiar ground surface which was scarcely observable around 3.0% Fe_3C and observed at 6.7% and 7.4% Fe_3C , was shown in Fig. 8 as the

Work speed $v=6\text{m/min}$
Depth of cut $d=50\mu\text{m}$

Fig. 8 Some typical examples of ground surface in the range of 6.0~8.0% Fe_3C .

example for clarifying the actual condition. First, the oxide film represented by the burn mark due to grinding was observed at 6.7% Fe_3C , and the internal structure turned out to be a cracking of tortoise shell shape. Similarly, as the peculiar observing aspect around this range, the unevenness of ground surface deemed to be caused by the occurrence of chattering was observed. Besides, as seen in the example of 7.4% Fe_3C , as example of such grinding damage considerably different from the so-called formation of ground surface determined geometrically was observed, in which steps were formed in the

grooves of grinding streaks as abrasive grains fell off in the midst of the grinding process. The reproducibility of such peculiar phenomena is low in the regular formation of ground surface represented by the streaks of abrasive grains, but appearance rate was high as compared with those on the materials with about 3.0% Fe_3C . On the other hand, corresponding to this change, the amount of plastic flow of the structure of ground surface layer (ℓ_f) and its depth (d_f) were measured and summarized in relation to the increase of Fe_3C amount, then ℓ_f and d_f showed the tendency of gradual decrease. However also in the range of similar Fe_3C amount, the increase and decrease of ℓ_f and d_f occurred, and ℓ_f and d_f decreased by about (10-20)% at about 3.0% Fe_3C but increased somewhat in the range of (6.0-8.0)% Fe_3C . Thus, when respective changes in the residual stress, hardness and structure of the ground surface layer in $\alpha\text{-Fe-Fe}_3\text{C}$ alloy were rearranged with the amount of Fe_3C as a parameter, it was found that a definite corresponding relation held. Also it was clarified that the definite corresponding relation to respective factors representing grindability held similarly.

5.2 Grinding chips and residual stress in ground surface layer in relation to the amount Fe_3C

For obtaining the information on grindability including ground surface layer, the studies are carried out⁽⁵⁾ from the relation among workpieces, grinding wheels and chips, but it would become very difficult to discuss the grindability with, say, chips only. However in some other fields, spark test has been empirically established for determining the carbon content in steels. Accepting such long-established facts, the relation among work, grinding wheels and chips was reviewed. First, chips were classified into flow type, shear type, molten type, and tear type.⁽⁴⁾⁽⁵⁾ Namely collected chips were divided into four types, and the proportion of respective numbers in the same amount of chips was determined and rearranged in relation to the amount of Fe_3C , thus the result in Fig. 9 was obtained. This result corresponds to the residual stress on ground surface being lowest at

Fig. 9 Frequency in the four types of grinding chip as a function of Fe_3C amount.

3.0% Fe_3C and highest at (6.0-8.0)% Fe_3C . Namely such tendency was observed when the flow type and shear type chips were ejected. And then, abrasive grains are very sharp in the range where the residual stress became lowest. And also, in the range where the residual stress became highest, the flow type and shear type chips decreased remarkably. After all, the proportion occupied by the molten type and tear type chips increased at the time of deteriorating grindability. As the amount of Fe_3C increased further and the matrix was embrittled, the shear type chips were ejected, but in most cases, more than half was occupied by the mixed presence with the tear type. On the other hand, the elongation and the contraction of area of matrix decreased in relation to the increase of Fe_3C amount, and it is conceivable that hard and brittle chips are formed mostly due to the presence of hard and brittle Fe_3C . The hardness of flow type, tear type and shear type chips increased gradually as the amount of Fe_3C increased, as shown in Fig. 10. However, in the case of molten type, the hardness was about $\text{Hv} = 500 \sim 600$ and constant regardless of the amount of Fe_3C accordingly it

Fig. 10 Changes of the chip hardness as a function of Fe_3C amount.

was excluded. At the time of measuring the hardness of chips because the sizes of chips are about 20-100 μm in breadth and thickness, while the diagonal length of the indentations of hardness testers is about 10 μm , various effects can not be considered in the present experiments.

Also it was found that the change in the proportion occupied by each morphology of chips corresponded similarly to the change of respective grindability factors improved when Fe_3C was at about 3.0% and deteriorated at (6.0-8.0)%.

5.3 Relation to number of cycles of grinding

The residual stress, hardness and structure of ground surface layer mentioned so far are the case of the formation by grinding only once. Now, the re-

residual stress on ground surface was shown in relation to the number of cycles n of grinding, then it was found that the residual stress continued to increase gradually with the number n , as seen in Fig. 11. This tendency was similar to the case of grinding using different kinds of grinding wheels under other grinding conditions. The residual stress in ground surface layer produced by one grinding cycle can be determined by numerical calculation through simulation, if the macroscopic Young's modulus E , work hardening coefficient H' , Poisson's ratio ν , specif-

Fig. 11 Residual stress of ground surface in relation to the number of times n of grinding.

ic heat ρ , and mean linear expansion coefficient of α -Fe works, the grinding temperature distribution and the resultant grinding force in ground surface layer, and the equivalent stress $\bar{\sigma}$ -equivalent strain $\bar{\epsilon}$ diagram of works are determined beforehand, and also the method according to the finite element method derived from the theory of elastoplastic mechanics by Yamada et al.⁽¹¹⁾⁽¹²⁾ is introduced. Accepting the examination result, the increase in residual stress seems due to the grinding temperature which continues to rise with the number n of grinding cycle, and it is presumed that the increase of tensile residual stress is produced on the basis of the increase of the grinding temperature. Accordingly, it is conceivable that the residual stress shifts gradually to tension side with the number n of grinding cycles owing to this process. Fig. 12 shows the result of measurement of

Fig. 12 Grinding temperature with the number of times n of grinding.

grinding temperature, and it is recognized that the rise of grinding temperature became remarkable at about $n=100$. On the other hand, normal and tangential grinding forces rose rapidly up to about $n=5$, but thereafter, they remained constant up to about $n=2000$ except under particular grinding conditions. Further, having reached $n=5000$, they were almost same as the values at $n=5$ although they showed only a slight rising tendency. On the contrary, the surface roughness, as shown in Fig. 13 showed a very large increase such as twice or thrice at a certain number of times n

Fig. 13 The roughness of finished surface vs. the number of times n of grinding.

as compared with the case of $n=1$. Similarly, this tendency is observed on the change of residual stress on ground surface. However, the relation between the surface roughness R_{max} and the change of grinding conditions at an arbitrary number of cycles of grinding was nearly equal to that known hitherto. Besides, the distribution of grinding temperatures extended over a wide region with an increase on n , and for example as shown in Fig. 14, a large difference appeared in the range of 1.0mm just below grinding point, having reached $n=5000$ from $n=1$, and a remarkable gradient of temperature drop occurred between them. At this time, the residual stress on ground surface reached up to about 80 kg/mm^2 when $d=20 \mu\text{m}$, and such value cannot be imagined from the former evaluation on α -Fe (211) surface, because it exceeded already the breaking stress of this material. At this time, the stress actually measured on Fe_3C (122) surface was about 550 kg/mm^2 , accordingly it reached the breaking stress of Fe_3C . Moreover, the expansion of region and the increase of fluctuating values and absolute values are brought about to the residual stress and the hardness distribution in ground surface layer when the number of cycles n of grinding is increased. For example, the hardness H_v and the hardened depth d_H at the ground surface with 14.1% Fe C were about $H_v=230$ and $d_H=60 \mu\text{m}$ at $n=1$, but reached $H_v=350\sim 400$ and $d_H=400\sim 450 \mu\text{m}$ at $n=3000$. The reason why the residual

Fig. 14. The distribution of grinding temperature with the increase of n .

stress exceeds the breaking stress, would be mainly ascribed to work hardening of work material. Besides, such change was observed similarly about the plastic flow l_f and the depth of flow d_f in the structure of ground surface layer.

The works were tempered materials, but when the speed v of the works and the depth of cut d were increased largely, a burn mark occurred on ground surface after about $n=3000$, and in some cases, the measurement of residual stress became impossible because of the formation of an amorphous oxide film. Anyway, apart from detailed correspondence, it is clear that the change in various factors of ground surface layer during one grinding cycle and also in n grinding cycles occurs corresponding to the change in the factors of grindability such as grinding force, grinding temperature and the surface roughness, and it can be known that the change in the factors of grindability and the change in the various factors on ground surface layer in n cycles of grinding correspond with each other in some extent.

6. Conclusions

The evaluation of the ground surface layer of $\alpha\text{-Fe-Fe}_3\text{C}$ alloy with (1.0–14.1)% Fe_3C was carried out by means of Fe_3C phase in relation to $\alpha\text{-Fe}$ phase. In short, it is said that the studies on metals have pursued the history of strengthening. The authors attempted first to clarify the relation with $\alpha\text{-Fe}$ phase, which has been the former criterion for evaluating ground surface layer, from the standpoint of the strong metallic grains of Fe_3C phase, which are the grains strengthening metals. Moreover, in order to make clear what relationships changes in the residual stress, hardness and structure of ground surface layer have with the factors representing grindability in relation to the amount of Fe_3C , mainly experimental investigation was carried out, and the following results were obtained.

(1) It was shown that the residual stress in such structure as microscopic Fe_3C phase can be measured with the X-ray equipment made for trial in the thin layer of every narrow range such as about 200 μm depth from ground surface and with large gradient and change of stress in that layer.

(2) Hitherto, the evaluation of the ground surface layer in $\alpha\text{-Fe-Fe}_3\text{C}$ alloy has been carried out by means of $\alpha\text{-Fe}$ phase. However, it was shown that the evaluation of ground surface layer on the basis of individual structure became possible by knowing the change of the main strengthening grains in the alloy.

(3) As the amount of Fe_3C increased, the dispersion of the stress σ_{RC} reduced gradually, and when it exceeded 10%, the residual stress ratio $\sigma_{\text{IC}}/\sigma_{\text{IF}}$ of Fe_3C and $\alpha\text{-Fe}$ phase showed the relation of $|\sigma_{\text{IC}}/\sigma_{\text{IF}}| = 4 \sim 5$. Besides, σ_{IC} took a very large value which was known in $\alpha\text{-Fe}$ phase hitherto.

(4) Both the fluctuating value and the distribution depth of residual stress in ground surface layer increased as the grain diameter $\bar{d}_0$ of Fe_3C and the grain diameter $\bar{d}$ of $\alpha\text{-Fe}$ became larger. Even when $\bar{d}$ and $\bar{d}_0$ changed, the relation in (3) holds. Besides, the fluctuating value and the distribution depth of residual stress in lamellar Fe_3C phase were larger as a whole as compared with those of spheroidized Fe_3C phase.

(5) In relation to the amount of Fe_3C , the residual stress on ground surface became smallest at about 3.0% of Fe_3C , and largest at (6.0–8.0)% of Fe_3C , but also various factors representing grindability changed corresponding to it. Moreover, the proportion occupied by four types of chips in total number respectively showed also a change corresponding to it, observing the change as a whole altogether a slight deviation existed. The flow type and shear type chips showed the corresponding change to the former in almost the same range of Fe_3C amount, and the molten type and tear type chips did the same to the latter.

(6) The increase in hardness and the depth of work hardened layer, and the amount of flow l_f and the depth of flow d_f

of the structure in ground surface layer also showed the corresponding relations mentioned in (5), and the increase and decrease occurred in the same Fe_3C range.

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