The Electrical Resistivity of the Dual Phase Steel
of Fe—29. 37 Ni—0.10C (WT%)

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Abstract

The electrical resistivity of the austenite and martensite mixture produced in both quench or sub—zero (an abridged term of QS is used hereafter) treatment and tensile plastic deformation is shown to agree well with the logarithmic mixture rule, varying its deviation coefficient, κ, in between plus and minus unities. The variation of κ is discussed in terms of the amount of plastic deformation and the dislocation motions in the austenite matrix of the mixture. The volume fraction of martensite in the mixture, produced in the latter, is examined to be predicted by the modified relation of the velocity of an autocatalytic chemical reaction (abbreviated as VACR) as well as the relation of the shear band intersection mechanism (abbreviated as SBIM). Here the former is employed to express the experimental results simply because of two coefficients needed to be determined and because of the fact that this steel transforms more or less in a burst type. The logarithmic mixture rule and the modified relation of VACR lead to an expression that the electrical resistivity— change of the mixture is a function of plastic strain, and the experimental variations are consistent with this.

INTRODUCTION

A lot of work has been carried out on the measurement of the electrical resistance of various steels during the martensitic transformation, which have examined the change in resistance or resistivity with respect to time and temperature [references (1), (2), for example]. McReynolds[3] has shown the relationship between the resistance of the austenite and martensite mixture and the volume fraction of martensite in the experiment of cooling a steel from about 300°C. His upper limit is given with the linear relation by linking the martensite entirely in series with the austenite and the lower limit with the non—linear relation by their linkage entirely in parallel, and the resistance of the mixture is shown to be given in between them. However, the relation does not take into account the effect of deformation involved and the experimental results in this study are not expressed accurately by it. The martensitic transformation produced in QS—treatment and deformation contains several kinds of lattice defects in addition to elastic strain, all of which affect the resistivity of the material. The recovery process of quenched and deformed metals[4],[5] is usually controlled by the activation energy and the temperature concerned, and it takes less time, the lower the activation energy at a specific temperature. Our preliminary tests exhibited that the resistance of the steel quenched and restored at 20°C decreased rapidly in a short time and reached asymptotically a relatively stable value after a longer period of time ($\fallingdotseq$ 60 min), the variation of which best fits the function of time decreasing in a hyperbolic manner. The data reported here are that measured after $\fallingdotseq$ 60 min and the

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change of resistivity with time is negligibly small compared with the one due to the martensitic transformation.

The resistivity of a non—ferrous metal mixture of Sn—Cd, for example, is expressed by the logarithmic mixture rule where the deviation coefficient, κ, is smaller than unity.[6] We apply this non—linear relation to the dual phase steel of austenite and martensite with κ varying in between ± 1, and the best overall agreement between the expression and the experimental results as a function of the volume fraction of martensite produced in QS—treatment and deformation is obtained. The variation in κ is discussed with respect to the plastic strain and the dislocation motions mainly in the austenite matrix of the mixture in the deformation induced transformation.

The volume fraction of the deformation induced martensite is examined to be represented with both relations of the modified VACR and SBIM. Here we employ the former from the fact that this steel transforms into martensite more or less in a burst type and also that it is simple in requiring only two coefficients (compared with three in the latter), although the relation is empirical and still lacks a theoretical basis. Using both the expression of the resistivity of the mixture as a function of the volume fraction of the deformation induced martensite and the expression of the volume fraction of the martensite as a function of the plastic strain, we have correlated the change in the resistivity of the mixture with the plastic strain, and fitting the experimental data to this expression shows good agreement for all tests at four different temperatures.

EXPERIMENTAL PROCEDURE

The thin sheet material of an Fe·Ni·C alloy, about 1 mm thick, was prepared through vacuum melting, hot and cold rollings, which contained 29.37 Ni, 0.10 C, 0.013 Si, 0.03 P, 0.03 S and 0.001 Mn (wt%) as constituents. Specimens having the parallel sections of 50 mm $\times 3.5$ mm $\times 1.0$ mm and 90 mm $\times 3.5$ mm $\times 1.0$ mm were carefully made and annealed in a vacuum capsule for 30 min , at 950°C. After X—ray examination of the complete austenite phase, the longer specimens were QS—treated under various conditions to get different amount of martensite. Tensile tests were performed on the shorter specimens using a small capacity machine of 4900 N with a special jig at the strain rate of $9.54 \times 10^{-4} \text{sec}^{-1}$. A full stress — strain curve to fracture was obtained at each temperature at the beginning, and then tensile tests in repeating load and unload steps $6 \sim 8$ times were performed on specimens to measure the electrical resistance and the volume fraction of martensite at each step. For the two phase analysis by X—ray diffraction, we employed $\{111\}_\gamma$ and $\{110\}_\alpha$ diffraction lines with C_O, K_α radiation. Linear analysis by micro—photographs was also added if necessary. The resistance was measured through the standard voltage—current generator (YEW, Type 2853), the current unit (YEW, Type 2862 with the current accuracy of $\pm 2\% + 0.1$ mA), the high precision digital voltage meter (YEW, Type 2501, 10^{-7} V). The exact current of 1.00000 A was arranged with the standard resistance (YEW, Type 2792, 0.01 Ω) and the potential difference was measured on specimens. For current junctions, thin copper leads were soldered at both ends of the gage section and, for voltage junctions thin pointed copper rods were gently contacted with springs on the specimen surface at a distance of $45 \sim 70$mm. All these were set in an isothermal room (20°C, 65% relative humidity), and the specimen with the junctions were again kept in a small transparent

isothermal box in the room to prevent any temperature change due to the close proximity of a human body. The potential difference was measured over a short period of time and the temperature variation at 20°C was ±0.0025°C. The dimensions of specimens measured exactly by a micron–micrometer at each time and the resistance and resistivity were calculated from potential difference in a usual method.

RESULTS AND DISCUSSION

[1] *The electrical resistivity and the volume fraction of martensite*

The time dependence of the resistivity of the specimen quenched from 950°C to -196°C and restored at 20°C shows the decrease in the hyperbolic manner and approaches a relatively stable value after a longer period of time. An example of this gives the resistivities at 20°C ; $\rho_{20°C} = 0.3459, 0.3434. 0.3421$ and 0.3314 mΩ·mm after the elapsed periods of 4, 30, 120 min and 423 days, respectively. The specimens cooled from room temperature to the various sub–zero temperatures show less changes than the above, and all these time dependences of the resistivity at 20°C are consistent with the relation given by $\rho_{20°C} = \rho_0 - at^b$ (t : min., ρ_0, a, b : const.). We reported here the data measured at a time later than about 60 min after the transformation and the time dependence of it is in a very small range of 0.14×10^{-4} mΩ·mm/min. On the other hand the resistivity change through the transformation from austenite to martensite reaches about to -5729×10^{-4} mΩ·mm at maximum. Thus the change in the former (if we fix the proper measuring time) is negligible compared with the one in the latter.

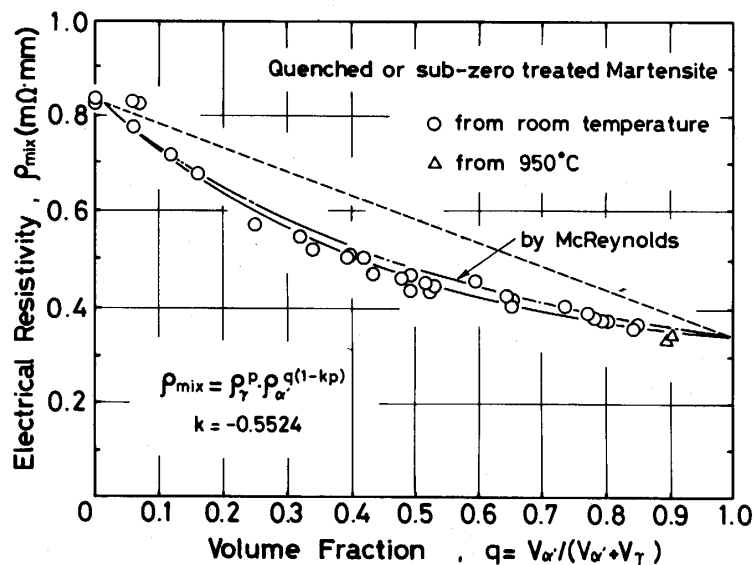Fig. 1 shows that the resistivity of the dual phase steel containing austenite and

Fig. 1   Relationship between the electrical resistivity and the volume fraction of QS–treated martensite. The linear and the logarithmic mixture rules are shown by the dotted and the solid lines, respectively. The one by McReynolds is indicated by a broken line.

martensite decreases with the volume fraction of the QS—treated martensite where the cooling conditions are changed to obtain the different amount of martensite. The dotted line indicates the linear rule given by

$$\rho_{mix} = p\,\rho_\gamma + q\,\rho_\alpha.$$
(1)

where ρ_{mix} : resistivity of the mixture

ρ_γ : resistivity of austenite

$\rho_{\alpha'}$: resistivity of martensite

p : volume fraction of austenite

q : volume fraction of martensite

The solid line shows the logarithmic mixture rule given by

$$\rho_{mix} = \rho_\gamma{}^p \cdot \rho_\alpha{}^{q(1 - \kappa p)}$$
(2)

where κ : deviation coefficient of -0.5524

This relation is a downward sloping convex curve compared with the linear rule. Here we determine κ and $\rho_{\alpha'}$ from the experimental values of ρ_{mix}, ρ_γ, p and q by computer. The experimental dependence of the resistivity on the volume fraction of the QS—treated martensite appears consistent with the relation given by Eq. (2). The broken line by McReynolds for the QS—treated martensite does not show the result accurately and it needs the $\rho_{\alpha'}$ value of 100% martensite in the beginning which is impossible in this case. The result of the deformation induced martensite tested in tension at $-29°C$ is given in the same manner in Fig. 2. The experimental variation of the resistivity measured at $20°C$ is consistent with the curve by Eq. (2) with $\kappa = -0.2685$. The relation is again a downward sloping convex curve compared with the linear rule. Fig. 3 is the result tested at $1°C$ and it
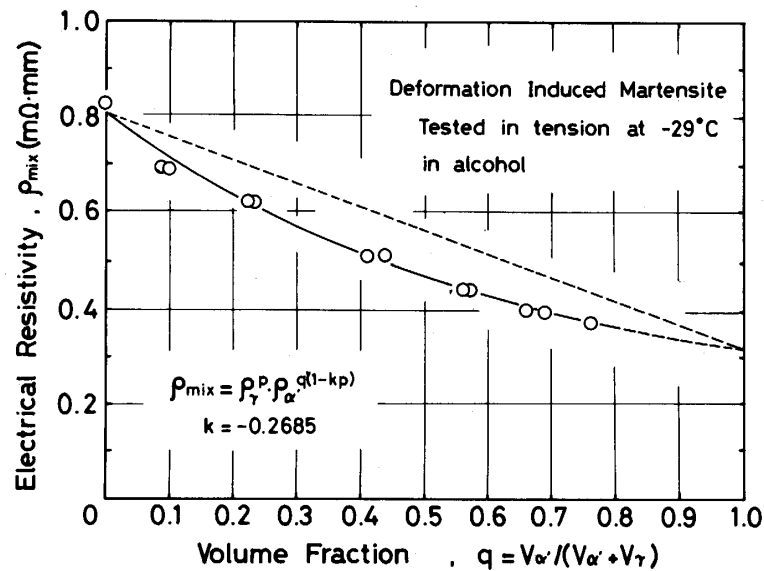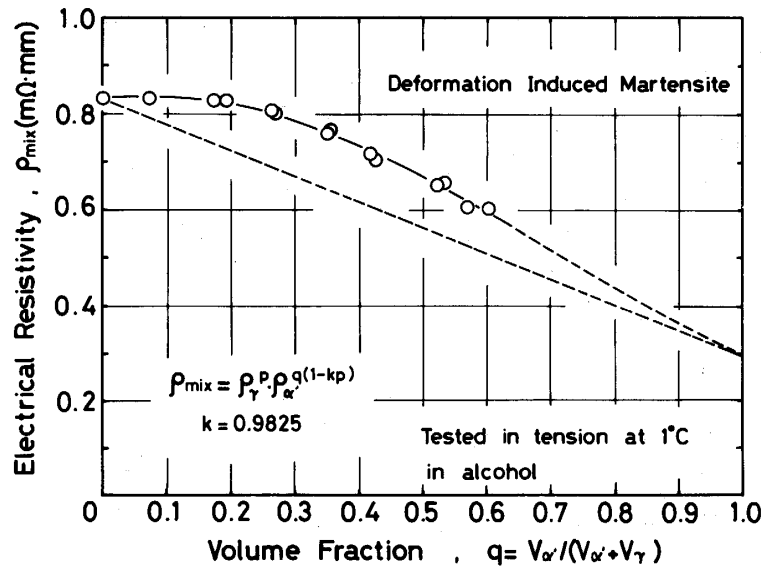

Fig. 2   Relationship between the electrical resistivity and the volume fraction of the deformation induced martensite at $-29°C$. The linear and the logarithmic mixture rules are shown by the dotted and the solid lines, respectively.

Fig. 3 Relationship between the electrical resistivity and the volume fraction of the deformation induced martensite at 1°C. The linear and the logarithmic mixture rules are shown by the dotted and the solid lines, respectively.

shows the upward sloping convex curve in contrast to the two previous examples and the solid curve is given by Eq. (2) with $\kappa = 0.9825$. The results at other test temperatures of -14 and -21°C are also consistent with the relations given by Eq. (2) showing the upward convex ($\kappa = 0.7434$) and the downward convex ($\kappa = 0.4206$) curves, respectively. Thus, the resistivity of the mixture containing austenite and martensite, where the latter phase produced either in quench or in deformation, can be expressed as a function of the volume fraction of martensite by Eq. (2) in which the deviation coefficient varies between minus and plus unities. This equation can also give the very close relation to the linear rule of the resistivity by choosing the κ value and we set this value as κ_0. The experimental variation of the deviation coefficient, κ, is plotted to the temperature difference, Δt, between the test temperature and the M_s point, in Fig. 4 and κ_0 value is also presented in the figure where the subscript 1 or 2 indicates the value obtained in the linear or the non–linear regression, respectively. The κ value increases with the temperature difference and the κ_0 value is nearly constant. This figure suggests that the resistivity of the deformation induced martensite on a steel may almost show the linear rule only at a fixed temperature, that is about -22°C in this steel. The κ and κ_0 values at $\Delta t = 0$ are the ones for the QS–treated martensite and these are different from others since no tensile plastic strain is experienced in this case.

When we determine the resistivity of the mixture, ρ_{mix}, from the experimental volume fraction of martensite, q, produced in QS–treatment or deformation, the difference in the ρ_{mix} value between using the logarithmic mixture rule and the linear rule is shown to be a function of q for the various test conditions in Fig. 5 (a). The difference in ρ_{mix} is the largest in negative for the -29°C test and the largest in positive for the 1°C test in the deformation tests and it changes from the downward convex to the upward convex curves depending
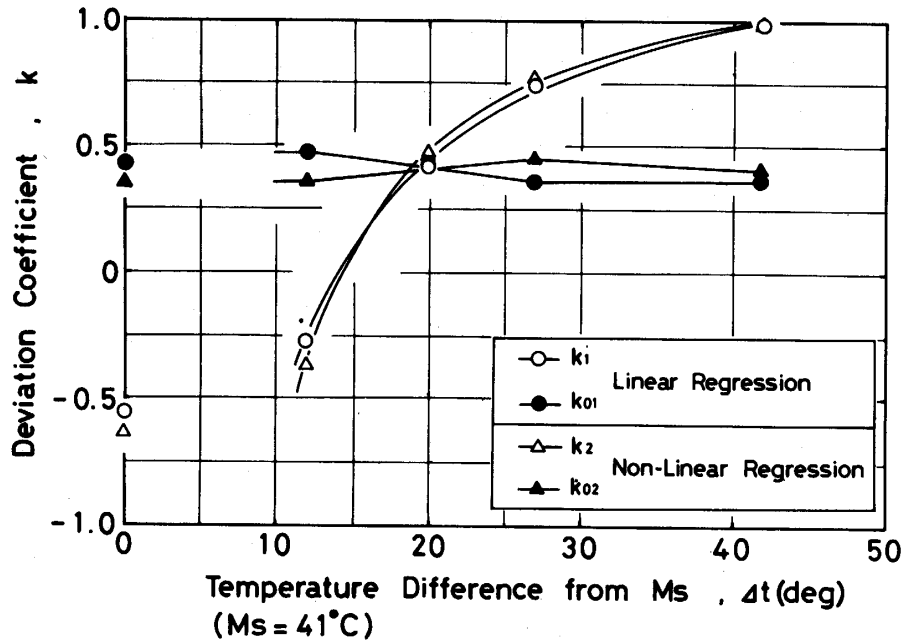
Fig. 4   Variation of the deviation coefficient (κ) with respect to the
temperature difference (Δt) from the M_s point, and κ_0 is the value
indicating the nearly linear rule in each test temperature. The sub-
script 1 or 2 shows the value obtained by the linear or the non-
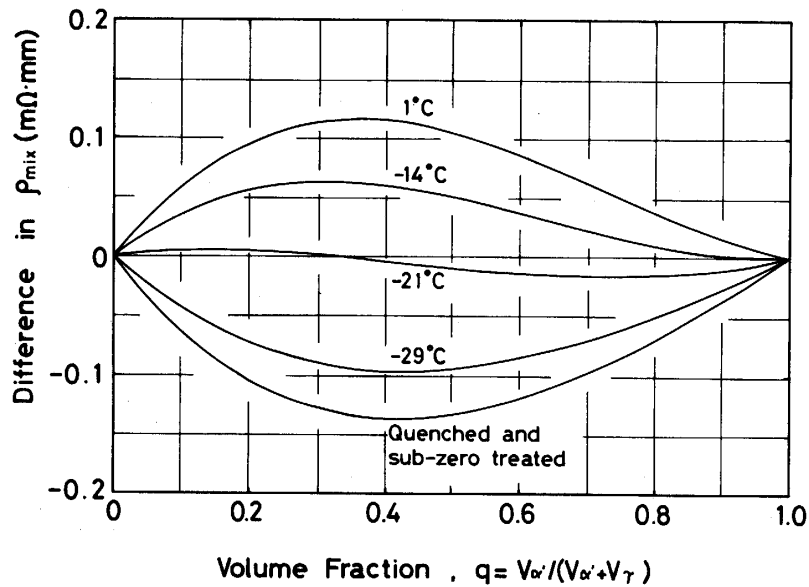linear regression, respectively.

Fig. 5 (a)   Difference [Eq. (2)–Eq. (1)] in the electrical resistivity, P_{mix},
in employing two rules to determine P_{mix} from the ex-
perimental volume fraction of martensite, q is plotted as a
function of the latter, where the test condition is different for
each curve.

upon the κ value. The QS–treated result with the smallest κ value, which is different from the other tests, shows the lowest curve in the figure. For the reverse case in determining the volume fraction of martensite from the experimental resistivity of the mixture, the difference in q in employing two rules is shown in Fig. 5 (b) for the various test conditions. The skew curves show the maximum difference of about $+22\%$ for the $1°C$ test and the minimum of about -20% for the $-29°C$ test in the deformation tests. These differences depend upon the κ value. The QS–treated result again shows the lowest value.

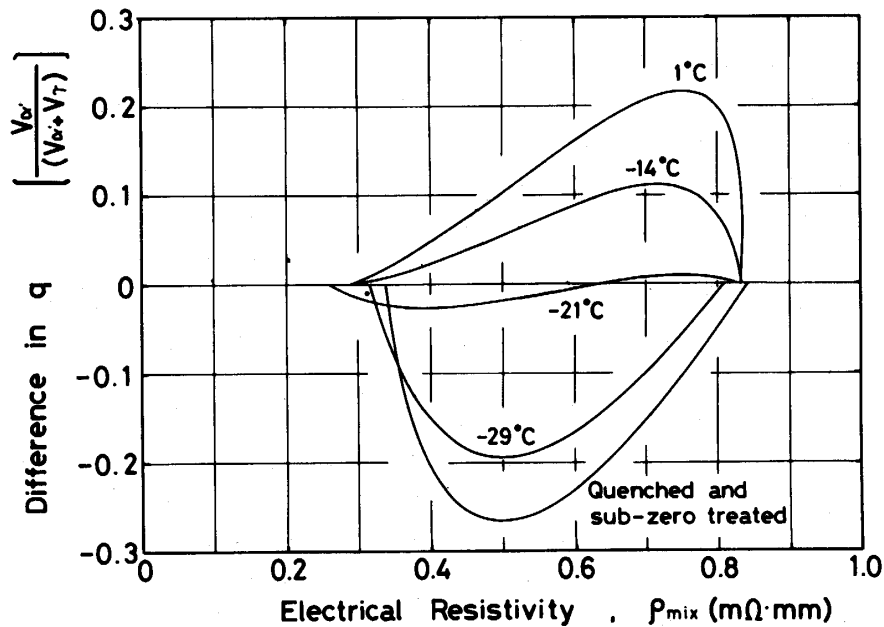We next discuss the κ value dependence on temperature in Eq. (2). The κ value is given[7] from Eq. (2)

Fig. 5 (b)   Difference [Eq. (2)–Eq. (1)] in the volume fracture of martensite, q, in employing two rules to determine q from the experimental electrical resistivity, ρ_{mix} is plotted as a function of the latter, where the test condition is different for each curve.

$$\kappa = \frac{1}{p} [1 - \frac{1}{q} (\frac{\log \rho_{mix} - p \log \rho_\gamma}{\log \rho_{\alpha'}})]$$ (3)

and it is chiefly governed by the ρ_{mix} value since both ρ_γ of the annealed 100% austenite and $\rho_{\alpha'}$ of the 100% martensite produced are almost constant at a specific temperature in a steel. The resistivity of the mixture in the deformation tests consists of the resistivities of the deformed austenite matrix and the induced martensite. The former is supposed to be strongly affected by the amount of the plastic deformation in the mixture because of its large plastic deformation and the latter is probably less affected because of its lesser plastic deformation compared with the former. We also know that a single phase specimen of austenite can deform plastically without fracture about ten times more in strain than that of

a nearly complete single phase specimen of martensite ($\alpha' = 0.893$) in this steel. In the tensile test through the deformation induced transformation, the specimen usually shows more elongation, including the transformation strain, than in the test without the transformation. This fact is clearly shown in Fig. 8 which is explained later. Thus the austenite matrix through the deformation induced transformation may experience much more elongation than in the case of the single phase. In this steel the austenite phase, having a relatively high stacking fault energy, usually deforms more by the movement of perfect dislocations in contrast to the one having a low stacking fault energy as 304 stainless steel which deforms rather by partial dislocations. The stacking fault energy is also reported to decrease with corresponding decrease in temperature, for example, the decrement of about $10 \, \text{ergs/cm}^2/100 \, \text{deg}$ on an Fe–18Cr–12Ni steel[8] at around room temperature. Meanwhile the martensitic nucleation theory by Olson and Cohen[9] predicts that some perfect dislocations in fcc are dissociated into coherent partial dislocations through the dissociation of perfect dislocations into Shockley partial dislocations, which nucleate the martensite with the association of other anti–coherent partial dislocations. The stacking fault energy of this steel will also change its magnitude with temperature and will affect the dislocation motions in the austenite matrix, and hence it would affect the nucleation of martensitic embryos. According to Fig. 8 (explained later), it exhibits that for a fixed volume fraction of martensite produced, for example $q = 0.6$, the plastic strain needed at $-29°C$ is 0.15 and the one at $1°C$ is 0.5 which is about 3.3 times larger than the previous. This is probably due to the fact that the specimen (i.e., the austenite matrix) deforms with more perfect dislocations, the higher the temperature (increasing also the stacking fault energy a little), and results in there being a lesser chance of nucleating martensite. Consequently it requires a large plastic strain to produce a fixed amount of martensite. The reverse case shows similarily that the austenite matrix deforms more, dissociating into coherent partial dislocations through Shockley partial dislocations, the lower the temperature (also decreasing the stacking fault energy a little). It also has a greater chance of producing martensite embryos, and therefore it needs less plastic deformation to produce the martensite. In the former process, the larger plastic strain in the austenite matrix with increasing the density of perfect dislocations increases the values of ρ_{mix} and hence κ. In the latter process, the smaller plastic strain in the austenite matrix with decreasing the density of perfect dislocations (and possibly including the density of partial dislocations not associated with the nucleation of martensite) decreases the values of ρ_{mix} and hence κ. On the other hand, the ρ_α' value, the resistivity of induced martensite which contains many deformation twins, is small to be about $0.37\rho_\gamma$. This phase experiences lesser deformation than the austenite matrix in the deformation induced martensitic transformation and its contribution to the increment of κ is small. The κ value for the QS–treated martensite is the lowest in this steel and this condition represents the least strained effect due to the transformation.

[2] *Relations among the martensite content ratio, plastic strain and change in the electrical resistivity*

The volume fraction of the deformation induced martensite on 304 stainless steel is given as a function of the plastic strain by the equation[10] of the VACR[11] type, with strain substituted for time

$$\frac{f}{1-f} = K \, \varepsilon_p^n \tag{4}$$

where f : the fraction transformed

ε_p : true strain

This relation requires two coefficients K and n to be determined. The relation by SBIM,

$$f^{\alpha'} = 1 - \exp\{-\beta[1-\exp(-\alpha \varepsilon_p)]^{n_1}\} \tag{5}$$

where $f^{\alpha'}$: the volume fraction of martensite

ε_p : plastic strain

is shown to express the experimental results on 304 stainless steel more clearly than the above[12] and this needs three coefficients α , β , n_1 to be determined. We examined the two equations to see how they expressed the experimental results on this steel. The volume fraction of martensite induced in the tensile test at $-14°C$ is shown to be a function of the plastic strain in Fig. 6. The relations given by the modified equation of VACR (the solid line) and SBIM (the dotted line) are also given, where the modified equation of VACR is given by the rearranged form of Eq. (4) as,

$$q = \frac{K \, \varepsilon_p^n}{1 + K \, \varepsilon_p^n} \tag{6}$$
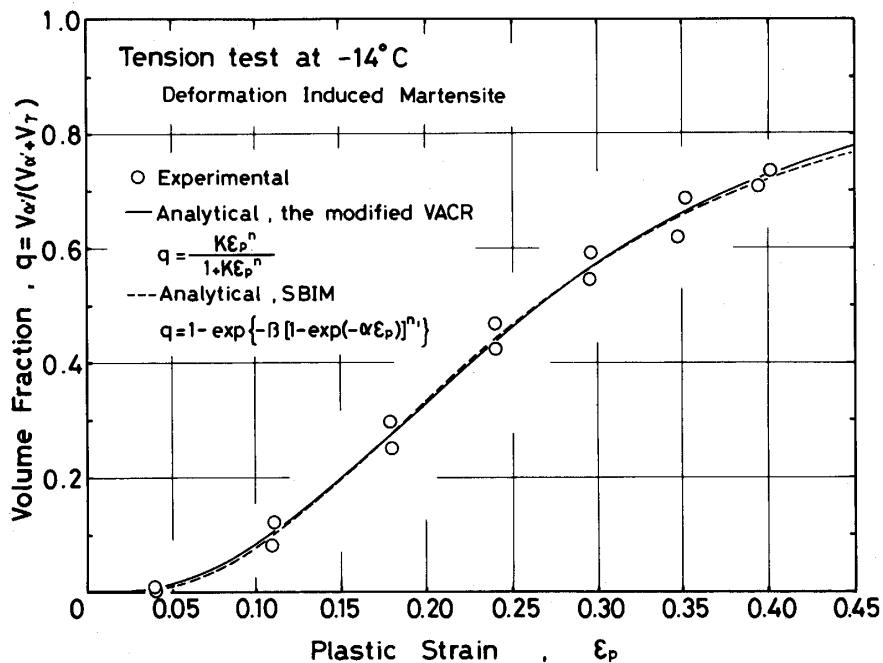

Fig. 6   Volume fraction of the deformation induced martensite, q, is plotted to the plastic tensile strain (ε_p) at $-14°C$. The solid and the dotted lines are given by the modified relation of VACR and the relation of SBIM, respectively.

q is the volume fraction of martensite and ε_p is true plastic strain, where the K and n values in Eq. (6) are determined to be 24.5 and 2.41 respectively. The values of α, β, n_1 in Eq. (5) are 4.13, 2.50. 3.13 in order. Experimental data appear consistent with both relations if we realize the difficulty in determining the martensite content ratio exactly. Here we employ the modified equation of VACR because it is simple in requiring two coefficients compared with three in the other and this steel also transforms more or less in the burst type. The relation between the volume fraction of martensite and the plastic strain is shown in Fig. 7(a) for the tests at four different temperatures, and all the experimental results are consistent with the
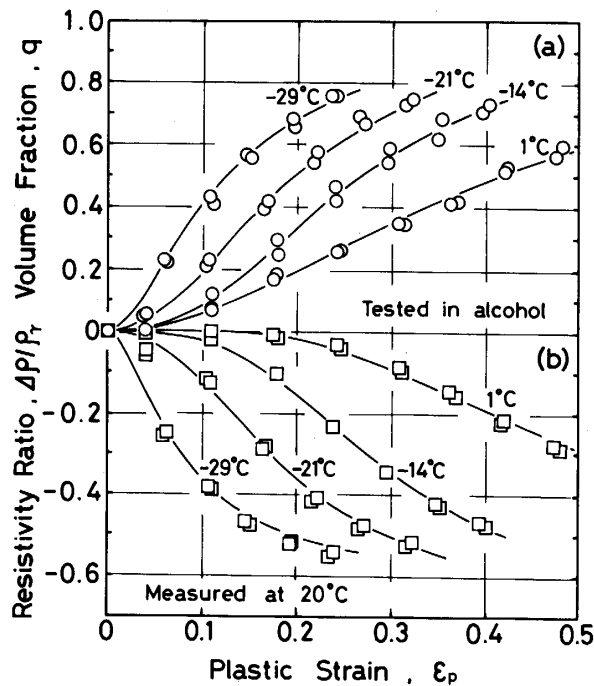

Fig. 7

The volume fraction of the deformation in-duced martensite [Fig. 7 (a)] and the change in the electrical resistivity ratio [Fig. 7 (b)] are plotted as functions of plastic strain. The solid lines are the relations by Eq. (6) in Fig. 7 (a) and by Eq. (7) in Fig. 7 (b), respectively.

solid curves by the modified equation of VACR. The K and n coefficients at the other temperatures are ($K = 32.3$, n $= 1.68$) at $-29°C$, $(32.7, 2.14)$ at $-21°C$, and $(5.80, 1.97)$ at $1°C$. The K value shows some decrease with an increase in temperature and the n value is nearly constant. The volume fraction of the deformation induced martensite is thus expressed by the simple function of plastic strain, Eq. (6). The resistivity of the mixture is also expressed as the function of the volume fraction of martensite produced by Eq. (2), thus these two equations lead to the expression that the change in the resistivity of the mixture is a function of the plastic strain,

$$\frac{\Delta \rho}{\rho_\gamma} = \frac{\rho_{mix} - \rho_\gamma}{\rho_\gamma} = \rho_\gamma{}^{p-1} \cdot \rho_\alpha{}^{q(1-\kappa p)} - 1 \tag{7}$$

$$\text{where} \quad q = \frac{K \varepsilon_p{}^n}{1 + K \varepsilon_p{}^n}$$

The experimental results for four different temperatures in Fig. 7 (b) give good agreement with the solid curves by Eq. (7).

All the described relations Eqs. (2), (6) and (7) among the resistivity of the mixture, ρ_{mix}, the volume fraction of martensite produced in QS–treatment and deformation, q, and the plastic strain, ε_p, exhibit the experimental results satisfactorily and they are represented in the three dimensional diagram in Fig. 8. The ρ_{mix} value varies with increases in both q and ε_p. The result in QS–treatment, which is not deformed in tension, is shown in the $\rho_{mix}-q$ surface and the relation in this surface is given by Eq. (2). The one in the $q-\varepsilon_p$ surface is given by Eq. (6) and the one in the $\rho_{mix}-\varepsilon_p$ relation is given by the compound equation of Eqs. (2) and (6), i.e.,
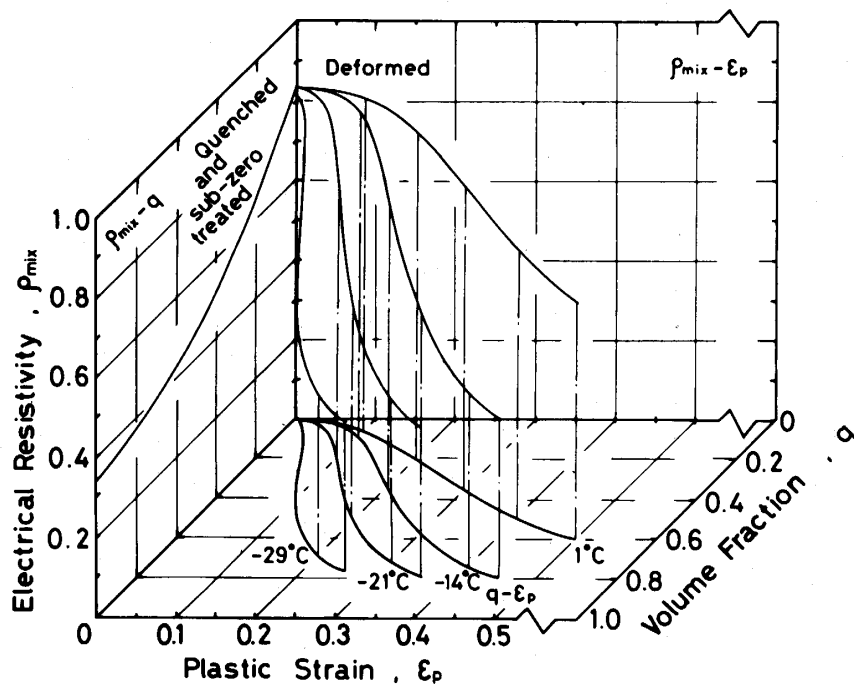

Fig. 8   The three dimensional diagram is constructed to present the varia-
tion of ρ_{mix} with respect to the volume fraction of martensite, q, and
the plastic strain, ε_p, and the relationships of $\rho_{mix}-q$ by Eq. (2),
$q-\varepsilon_p$ by Eq. (6) and $\rho_{mix}-\varepsilon_p$ by Eq. (8) are shown.

$$\rho_{mix} = \rho_\gamma^{\frac{1}{1+K\varepsilon_p^n}} \cdot \rho_\alpha^{\frac{K\varepsilon_p^n}{1+K\varepsilon_p^n}(1-\frac{\kappa}{1+K\varepsilon_p^n})} \tag{8}$$

This steel exhibits the deformation induced transformation at the temperatures shown and no data appears in the $\rho_{mix}-\varepsilon_p$ surface.

The results given above are based on the X–ray data by the well–known single–peak diffraction method for each phase as mentioned previously. All the relationships here give the correct tendencies although some corrections will be needed if one employs a more exact two–phase X–ray analysis such as a special multiple–peak analysis for each phase. We are working on it and their results will be reported recently.

CONCLUSIONS

The electrical resistivity at 20°C of the mixture on an Fe–29Ni–0.1C(wt%) steel was investigated as functions of the volume fraction of martensite produced in QS–treatment and deformation and the plastic tensile strain at various temperatures. The following conclusions are drawn.

The resistivity dependence of the mixture on the volume fraction of martensite produced gives good agreement with the logarithmic mixture rule where the deviation coefficient, κ, is changed between negative and positive unities, and its variation is mainly controlled by the amount of the plastic strain and the dislocation motions in the austenite matrix of the mixture. The same rule with a different value of the deviation coefficient, κ_0, also corresponds very closely with the linear relation. The linear rule is useful to express the relation between the resistivity and the volume fraction of martensite only at a specific temperature for a fixed constituent steel where $\kappa = \kappa_0$.

The volume fraction of the deformation induced martensite is consistent with the relations given by the modified equation of VACR in which the K value decreases with increasing temperature and the n value is nearly constant. Since the experimental variations of relations, $\rho_{mix}-q$ and $q-\varepsilon_p$, in this study are consistent with both relations of the logarithmic mixture rule and the modified equation of VACR, respectively, these lead to an expression that the resistivity change of the mixture is a function of plastic strain. The experimental results appear consistent with this expression. The three dimensional diagram of the resistivity of the mixture, ρ_{mix}, the volume fraction of martensite produced in QS–treatment and deformation, q, and the plastic strain ε_p, indicates that the resistivity of the mixture varies considerably with corresponding increases in both ε_p and q.

ACKNOWLEDGEMENTS

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