HOT DEFORMATION BEHAVIOUR OF 3% SILICON STEEL UNDER WEDGE SHAPED SPECIMENS

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Résumé

Le comportement de la recristallisation statique d'un acier à 3% de Silicium à bas carbone qui représente la phase ferritique à des températures élevées a été examiné en utilisant des essais de laminage à chaud à une seule passe.

Les essais de laminage à chaud étaient réalisés à une température de laminage de 900°C jusqu'à une épaisseur finale de 900mm, suivi par un maintien à la même température de laminage.

Le volume recristallisé augmente avec l'augmentation de la réduction par laminage à chaud et le temps de maintien après laminage. La zone privilégiée pour cette recristallisation était les joints des grains précédents, en particulier les points triples des joints ou la déformation était bien concentrée. Dans ce matériau à taille de grain fine, la possibilité d'avoir des résultats compatibles lorsqu'en utilise un matériau qui la forme d'une cale, nécessite un contrôle dominant de la déformation et de la température de déformation.

ملخص

سلوك اعادة التبلور الاستاني لفولاذ ذو3% من السيليكون منخفض الكربون الذي لديه البنية الفريتية عند درجات حرارة مرتفعة، تمت عليه عملية البحث وذلك باستعمال تجارب الدرفلة على الساخن ذات ممر واحد.

استعملت تجارب الدرفلة على الساخن عند درجة حرارة قدرها 900°م وذلك حتى 9 مم سمكا، متبوعة بتثبيت في فرن عند نفس درجة الحرارة (900°م) وهذا، باستعمال عينات من قضيبين مسحوبين. الحجم المعاد التبلور يزداد مع الزيادة في التخفيض الدرفلي، ووقت تثبيت الحرارة بعد الدرفلة.

المنطقة المفضلة لاعادة التبلور كانت الحدود السابقة للحبيبة خاصة النقاط الحدودية الثلاثية أين كان التوترمركزا.

في هذه المادة ذات الحجم الحبيبي الدقيق، امكانية الحصول على نتائج مقبولة تحتاج الى مراقبة أحسن للتوتر و درجة الحرارة، و هذا عند استعمال عينات ذات قطاع اسفيني.

Abstract

The static recrystallisation behaviour of a low carbon 3% Silicon steel, which is ferritic at high temperatures, has been investigated using a single-pass hot rolling experiment. The hot-rolling tests were carried out in a temperature of 900°C to 9mm thickness followed by holding at the same temperature, using specimens of the two extruded bars. With increasing rolling reduction and holding time after rolling, the fraction recrystallised increased. The preferential area for this recrystallisation was the previous grain boundaries, particularly triple points of boundaries where the strain was concentrated. In this fine grain size material, the possibility of consistent results needs better control of strain and temperature under the wedge shaped material.

***Key words**: 3% Silicon steel, hot rolling, dynamic recovery, static recrystallisation.*

INTRODUCTION

Recrystallisation studies have shown that 3% silicon steel as well as ferritic stainless steels have slow kinetics of recrystallisation [1,2] and therefore are a good choice to perform experiments without the intervention of recrystallisation.

Many investigators have used silicon-Iron as an experimental vehicle for the study of deformation and annealing phenomena in body-centered cubic materials for the reason that electrolytic etching of a Si-Fe alloy reveals dislocations and s
ubstructure in unrecrystallized grains. This unique characteristic makes possible a precise determination of the extent of recrystallisation.

Many workers have investigated the development of structure and texture during hot rolling of commercial 3% Silicon steels. It is found that structural heterogeneity develops mostly at that stage of deformation, which is not accompanied by the development of recrystallisation right through the cross section of the slab. The texture and structure state are different in the surface and central layers.
In this series, wedges of ferritic 3¼% Silicon steel were rolled to obtain basic information about the recrystallisation behaviour of this material. With this aim, a series of tests was carried out to find the effective strain to use where recrystallisation would occur in a convenient time, and therefore to know the range of time where there is no fraction of material recrystallised. This will allow to know in a future use what is the effect of static recovery on the subsequent recrystallisation kinetics, in particular to evaluate the rate of recrystallisation after two passes in terms of the time for static recovery occurring before a second pass.

A few investigations have also been made on the recrystallisation behaviour in such specimens as 3% Si steel [3-5]. According to the previous investigations, the kinetics of static recrystallisation were also a function of the applied strain, and the dependence was significantly higher [3,4].

MATERIALS AND METHODS

The experiments were conducted on Silicon steel of chemical composition shown in table (1). This material was prepared in the Department of Engineering Materials, University of Sheffield; it was air-melted in a Birlec induction furnace at a temperature of 1580°C and cast to two hot-topped ingots of 76mm in diameter. The composition of the ingot analysis was chosen to conform with a typical commercial analysis, but with very low carbon content. The ingots were machined into round billets of 72mm in diameter, reheated to a temperature of 1150°C for 1 hour, and extruded using glass lubricant to rectangular bars with nominal cross section of about 28×15mm. After extrusion the material was of uniform recrystallised structure (Fig.1), with grain size of $233\pm 16\mu$m.

Table 1. Chemical composition of 3% Silicon-steel (wt%)

Element	C	S	P	Mo	Ni	Si	V	Cr	Mn	Nb	Ti	Co	Al	Cu
Base	0.014	0.004	0.004	0.02	<0.02	3.33	<0.02	<0.02	0.12	<0.02	<0.02	<0.02	0.028	<0.02

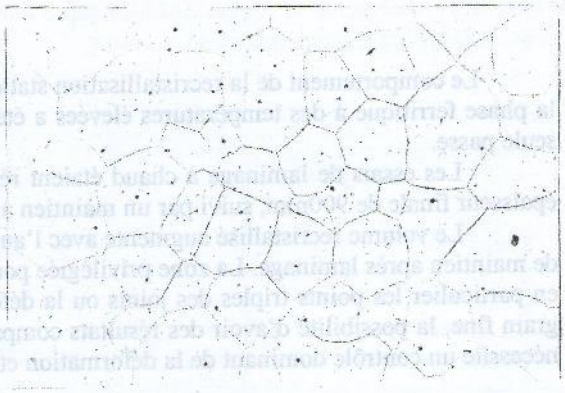


Fig.1. Optical micrograph of the as extruded structure of the experimental 3% ferritic Silicon steel.

Rolling tests were carried out on wedges of dimensions of 120×15mm with variation from 9 to 19mm thickness, using a fully instrumentated Hille 50 rolling mill. The rolling temperature was recorded using a 1.5mm diameter Pyrotenax Chromel-Alumel thermocouple which was inserted to the geometrical centres of the wedges. Wedges of 3% Silicon-steel were reheated for 15 minutes prior to each run in an electric resistance furnace in a protective atmosphere of exothermic gas produced by controlled combustion of natural gas. After reheating, the wedges were hot rolled at 900°C to 9mm thickness, followed by holding at 900°C for different annealing times and then water quenching immediately after annealing (t< 4s).

The equivalent true strain is given by [6];

$$\varepsilon=\frac{\sqrt{2}}{3}[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2]^{1/2} \quad (1)$$

ε_3 is the strain in the thickness direction given by;

$$\varepsilon_3 = ln(h_f/h_0) \quad (2)$$

h_0 and h_f are the initial and final thickness.

ε_2 is the strain in the width direction given by;

$$\varepsilon_2 = ln(W_f/W_0) \quad (3)$$

W_0 and W_f are the initial and final width.

ε_1 is the strain in the length direction given by;

$$\varepsilon_1 = -\varepsilon_2 - \varepsilon_3 \qquad (4)$$

`Metallography for 3% Silicon steel was carried out at several positions in which transversal sections (face X in Fig.2) were the areas to be observed in the microscope. After sectioning and linishing, specimens were ground down through successively finer Silicon carbide papers, 120, 400, 800, and 1200 grade. Afterwards they were polished on the 6, 1 and 1/4μm diamond metallographic wheels. The specimens were then electrolytically etched at a potential of 5 volts for 6 minutes using Morris's reagent containing: $25gCr_2O_3$, 133ml glacial acetic acid, 7ml water. The etching was done without stirring the solution and no cooling was required. After taking the specimen out of the solution, it was rinsed with water followed by methyl alcohol, and dried in hot air.

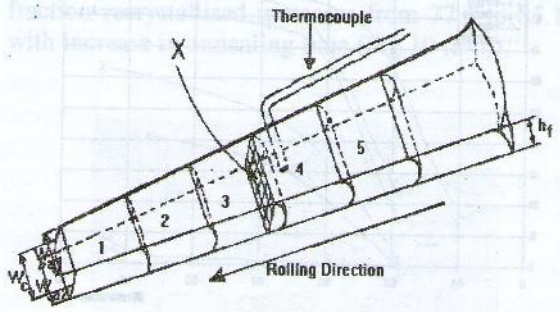


Fig.2. Schematic diagram of the deformed samples of 3% Silicon steel, the faces marked X were the planes taken for metallographic examination.

RESULTS

Examination of metallography microstructure of deformed and annealed Structure

Examination of wedges quenched immediately after the first pass showed deformed grains and no recrystallisation took place during deformation. Subgrain structure was clearly evident but difficult to resolve (Fig.3).

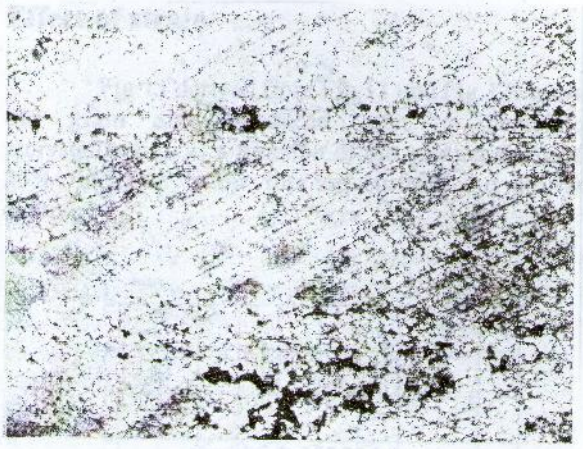


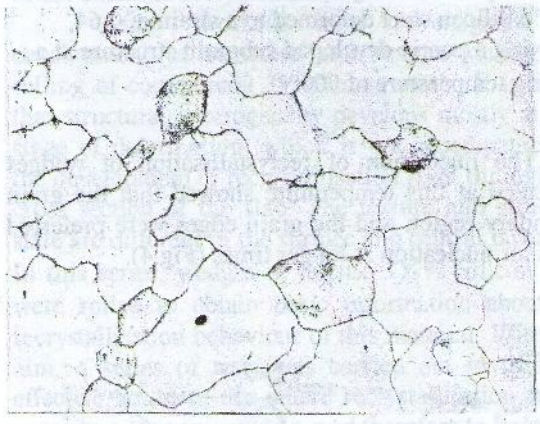
Fig.3. Optical micrograph of the deformed structure of 3% Silicon steel deformed to a strain of 0.64, showing a poorly developed subgrain structure at a rolling temperature of 900°C.

The nucleation of recrystallisation of wedges annealed at this temperature showed that the grain boundary region and the grain edges were preferred sites for nucleation at longer times (Fig.4).

Fig.4. Optical micrograph of material of 3% Silicon steel deformed to a strain of 0.64, at a rolling temperature of 900°C, and annealed at 900^0C for 40 sec, showing grain boundary region and grain edges as sites for nucleation.

Annealed wedges at longer times deformed to different effective strains at a hot rolling temperature of 900°C indicated that inhomogenieties of recrystallisation in the transverse sections through the thickness were observed (Fig.5 (a-b)). Therefore sections at 25% thickness below the top surface and at the centre of the deformed and annealed wedges were selected for standard examination.

(a)_25% thickness



(b)_Centre

Fig.5. Optical micrographs of 3% Silicon steel deformed to a strain of 0.39, showing variations in the volume fraction recrystallised through the thickness.

Relation between fraction recrystallised and annealing time

In order to determine the isothermal recrystallisation kinetics after deformation to different effective strain where dynamic recovery is the only restoration process during deformation, wedges of this material were deformed at temperature of $900^0 C$.

The experimental results of the tests are shown in Fig.6 and Fig.7 as volume fraction recrystallised, X versus effective strain of sections at 25% thickness below the top surface and at the centre respectively. Fig.8 and Fig.9 show the volume fraction recrystallised, X versus Log time of sections at the same depth indicated above derived from Fig.6 and Fig.7 respectively.

The recrystallisation curves for this fine grain sized material show that strain has a large effect on static recrystallisation rate over this range of conditions.

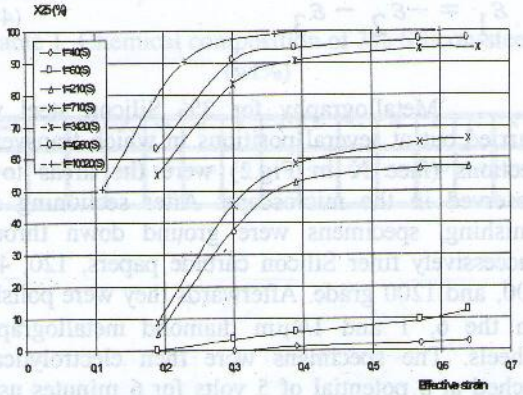


Fig.6. Relation between effective strain and volume fraction recrystallised at quarter thickness (25% thickness

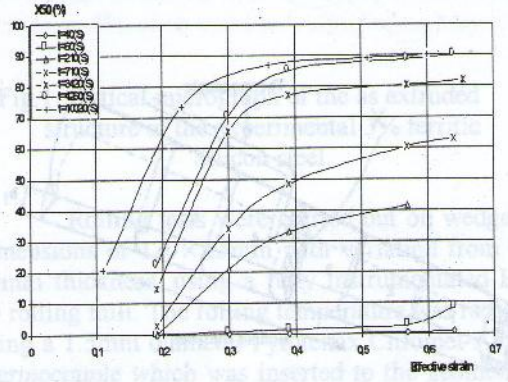


Fig.7. Relation between effective strain and volume fraction recrystallised at the centre (50% thickness).

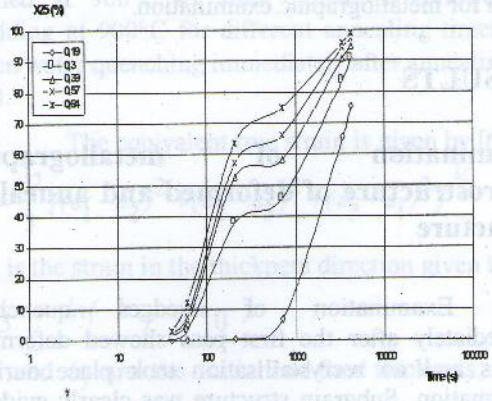


Fig.8. Isothermal recrystallisation curves of material of 3% Silicon steel at quarter thickness (25% thickness), deformed at a temperature of 900°C, d_0=233μm.

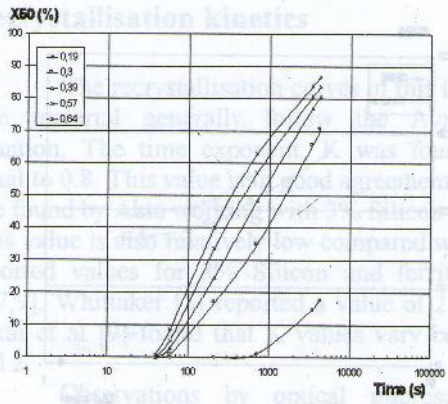
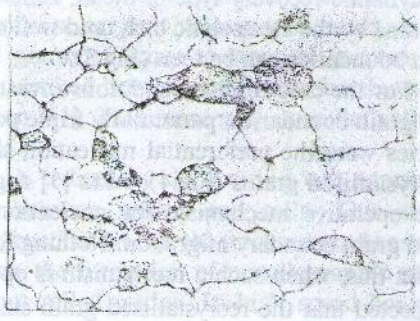


Fig.9. Isothermal recrystallisation curves of material of 3% Silicon steel at the centre (50% thickness), deformed at a temperature of 900°C, d_0=233μm.

The microstructure immediately after deformation to a strain of 0.64 (Fig.3) consists of deformed ferrite grain with a poorly developed subgrain structure. After a delay of 40 seconds some regions have statically recrystallised (Fig.4). Deformed microstructure to a strain of 0.39 after a delay of 3420 and 4260 seconds, showed that volume fraction recrystallised increases from 77.3 to 85.1% with increase in annealing time (Fig.10 (a-b)).

(a)-(Annealing time=3420 sec, X=77.3 %).



(b)-(Annealing time=4260 sec, X=85.1 %).

Fig.10. Optical micrographs showing variation of volume fraction recrystallised with annealing time.

Effect of strain

Fig.13 derived from Fig.11 and Fig.12 shows the grain size produced after a complete recrystallisation as a function of the applied strain at 25% thickness below the top surface and at the centre.

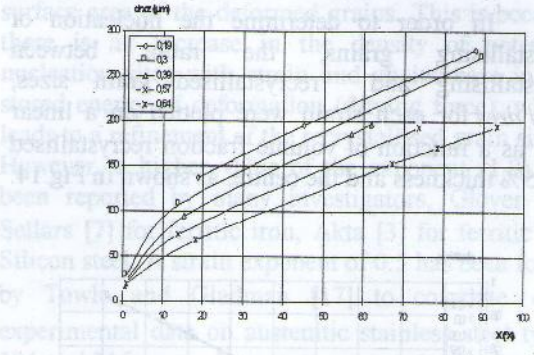


Fig.11. Relation between volume fraction recrystallised and recrystallising grain size at quarter thickness (25% thickness).

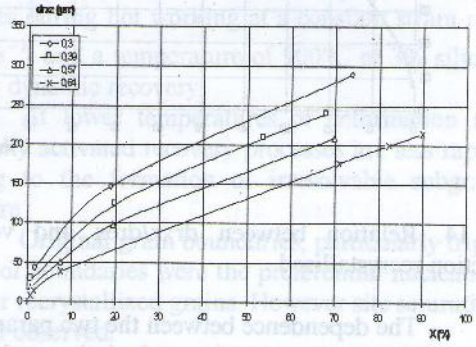


Fig.12. Relation between volume fraction recrystallised and recrystallising grain size at the centre (50% thickness

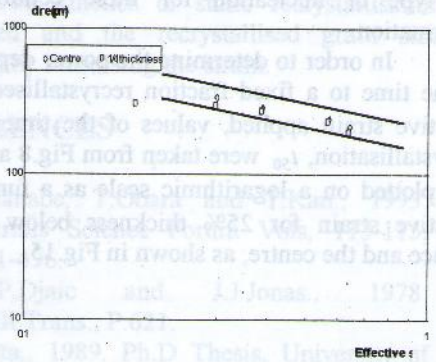


Fig.13. Effect of strain on recrystallised grain size in material of 3% Silicon steel, deformed at a temperature of 900°C, $d_0 = 233\mu m$.

The power dependence of the relationship between recrystallised grain size, d_{rex}, and effective strain has been found for isothermal tests in the range of effective strains (0.19-0.64) to be;

$$d_{rex} \propto \varepsilon^{-0.5} \qquad (5)$$

In order to determine the nucleation of recrystallising grains, the ratios between recrystallising and recrystallised grain sizes, *drxz / drex* for each strain were plotted on a linear scale as a function of volume fraction recrystallised for 25% thickness and the centre, as shown in Fig.14.

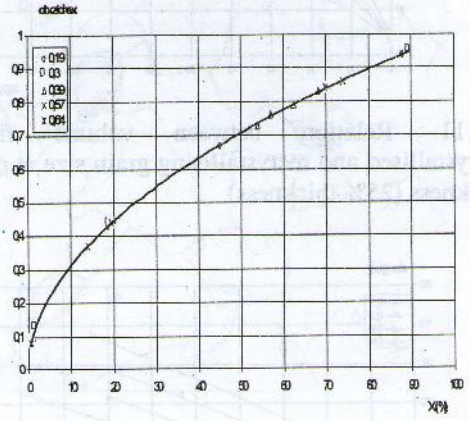


Fig.14. Relation between drxz/drex and volume fraction recrystallised.

The dependence between the two parameters does not follow the cubic form of relation and found to be;

$$\frac{drxz}{drex} \propto X^{1/2} \qquad (6)$$

Then according to this relation, site saturation is not the type of nucleation for these conditions of deformation.

In order to determine the power dependence of the time to a fixed fraction recrystallised on the effective strain applied, values of the time to 50% recrystallisation, t_{50} were taken from Fig.8 and Fig.9 and plotted on a logarithmic scale as a function of effective strain for 25% thickness below the top surface and the centre, as shown in Fig.15.

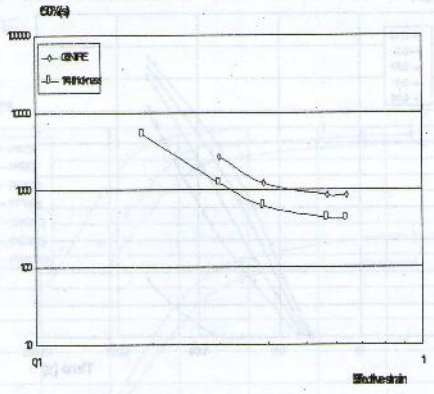


Fig.15. Effect of effective strain on time for 50% static recrystallisation in material of 3% Silicon steel, deformed at a temperature of 900°C, $d_0 = 233\mu m$.

The power dependence of the relationship between, t_{50} and effective strain has been found for isothermal tests in the range of effective strains (0.19-0.64) to be;

$$t_{50} \propto \varepsilon^{-2.5} \qquad (7)$$

When n decreases from about 2.5 towards zero with increase in strain.

DISCUSSION

Structural observations

In this discussion, the recovery process has been assumed to involve rearrangement and annihilation of lattice defects produced by the deformation. The microstructural features observed in specimens quenched immediately after deformation certainly indicated that the present steel behaved as a typical dynamic recovery type of metal. Line defects are revealed by the electrolytic etch, and well defined subgrain boundaries can be seen (Fig.3).

For the deformation conditions investigated, original grain boundaries, particularly triple points of boundaries were the preferential nucleation sites for new recrystallised grains (Fig.4). Akta [3] suggested that the operative mechanism for nucleation is by localized grain boundary migration. Nothing found to contradict this, when such a mechanism is operating it is expected that the recrystallised grain size, d_{rex} would be smaller than the original grain size, d_0, especially when the latter is relatively small and therefore the density of possible nucleation sites should be high [7,8].

Recrystallisation kinetics

The recrystallisation curves of this fine grain size material generally follow the Avrami-type equation. The time exponent, K was found to be equal to 0.8. This value is in good agreement with the one found by Akta working with 3% Silicon steel [3]. This value is also relatively low compared with other reported values for 3% Silicon and ferritic steels [5,7,9]. Whittaker [5] reported a value of 2 whereas Sakai et al [9] found that K values vary between 1 and 2.

Observations by optical microscopy on samples deformed to different strain at a start rolling temperature of 900^0C showed clearly that the first visible recrystallisation nuclei were situated at grain edges and at grain boundaries. This initiation stage was followed by rapid development of recrystallisation during subsequent annealing, which once again decreases before the completion of recrystallisation at high strain.

Effect of strain

The effect of increasing strain at lower strains is to increase the density of potential nucleation sites and increases the stored energy of deformation (driving force). The former leads to an increased migrating boundary area during recrystallisation and refinement of the recrystallised grain size, whilst the latter in a more rapid rate of recrystallisation as the strain increases. The value of negative strain exponent of 2.5 for the dependence of time for 50% recrystallisation in the range of effective strains [0.19-0.64] is lower than other results. Sakai and Ohashi [9], English and Backofen [4], Glover and Sellars [7], Akta [3] and Morrison [10] have all found n to be equal to 4. It is clear from a closer examination of the results that the time to 50 % recrystallisation decreases as the strain approaches the steady state. The acceleration of recrystallisation by strain even beyond the steady state condition can be attributed to the continuous increase in grain boundary area per unit volume with strain, since the original grains continue to elongate and boundaries become serrated between subgrains thereby assisting nucleation [11]. Thus more nuclei per unit volume are produced.

A redundant shear strain was generated by friction between wedge and rolls. This strain is inhomogeneous through the thickness and has marked effects on the formation of metallographic structure in the hot rolled wedge. In high speed hot rolling, shear strain tends to accumulate near the surface to form a severely sheared region, where a narrow layer of fine recrystallised grains is often observed when quenched into water quickly after rolling [12,13].
The redundant shear strain is also responsible for the texture variations through the thickness, because not only the rolling texture is affected by the shear strain but also the inhomogeneous recrystallisation (Fig.5 (a-b)) due to the inhomogeneous shear strain introduces additional inhomogeneity of the texture.
The recrystallised grain size d_{rex} is dependent on strain by the relation ($d_{rex} \propto \varepsilon^{-0.5}$). It is expected from previous work on recrystallisation in hot rolling [14-16] that the recrystallised grain size will be strongly dependent on the applied strain and the surface area of the deformed grains. This is because there is an increase in the density of potential nucleation sites with strain and an increase in the stored energy of deformation (driving force), which leads to a refinement of the recrystallised grain size. However, a higher value of the exponent (1.0) has been reported by many investigators, Glover and Sellars [7] for ferritic iron, Akta [3] for ferritic 3% Silicon steel. A strain exponent of 0.5 has been found by Towle and Gladman [17] to correlate d_{rex} experimental data on austenitic stainless steel types 304 and 316.

CONCLUSION

The dynamic restoration process which operates during hot working at a constant strain rate of $3.3\,s^{-1}$ and a temperature of 900°C of 3% silicon steel is dynamic recovery.

At lower temperatures of deformation the thermally activated recovery processes are less rapid, leading to the formation of irresolvable subgrain structure.

Original grain boundaries, particularly triple points of boundaries were the preferential nucleation sites for recrystallized grains. However site saturation was not observed.

Recrystallisation generally follows an Avrami type of behaviour with a coefficient, K≈0.8. The inhomogeneity of the recrystallisation due to shear strain in the hot rolled wedges may plays an important role in the manufacture of high quality metal. It gives origin of Goss texture in final products.

The kinetics of static recrystallisation is accelerated and the recrystallised grain size is decreased by increasing the strain.

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