선재압연에서의 TMCP 모사 모델

이 영석* · 주 웅용** · 김 성일*** · 권 정석**** · 정동원*****

1. INTRODUCTION

With a mathematical model, simulation of the pass-by-pass change of microstructure of material in hot rolling process is of special importance with respect to the control of mechanical properties of the products. Then, process designer's interest focuses on how to calculate the thermo-mechanical parameters that may be the strain, strain rate per pass and the temperature change of the material due to plastic deformation in the roll gap and cooling between inter-stand (pass), and to model the microstructual evolutio n such as recrystallization behavior(static or dynamic), AGS(austenite grain size) change and unrecrystallized volume fraction of material during rolling.

Hence, many mathematical models for the thermo-mechanical parameters have been proposed, coupled with a laboratory scale experiment(hot torsion or uni-axial com pression)-based microstructural evolution model, to predict microstructural state during rolling.[1-3] The evolution of pass-by-pass AGS were considered to be determined by the recrystallization (dynamic or static) and grain growth behavior during rolling, and have been formulated as a function of the temperature, strain, strain rate at a pass and initial AGS. Most of these works, however, have been concentrated on the strip (or plate) rolling process. A little research has been done on rod rolling process.

There has been strong demand to develop a mathematica l model, which is

*, ** 포항제철 기술연구소 후판연구그룹
*** 금속공학부, 인하대학교
**** 포항제철 선재부
***** 제주대학교 기계에너지생산공학부

of a simple form with reliable accuracy and non-iterative in computation, for obtaining the thermo-mechanical parameters(strain, strain rate and temperature) associated with rod(or bar) rolling process. The reason is that these parameters are key elements to predict AGS in rod rolling process because the recrystallization behavior and AGS evolution model developed for strip rolling can be applied directly to rod rolling. Thus, there have been several attempts [4-6] to develop the model associated with rod rolling.

Maccagno, et al.[4], in the study of pass-by-pass AGS evolution associated with oval-round(or round-oval) pass rolling sequence, calculated the strains by the simple multiplication of a constant factor to the area strains, which were obtained by taking the natural logarithmic of the ratio of the fractional reductions in cross-sectional area through the rolling stands. The strain at a pass was assumed to be a constant factor of 1.7 times the area strain for the roughing stands, and 2.5 times the area strain for the finishing stands. They simply attributed the necessity of these factors to occurrence of redundant strain related with the profile changes of workpiece during rolling such as oval-round or round-oval pass rolling. Kemp[5] proposed that the strain per pass should be factors of 1.5 to 2 times the area strains in the roughing stands and factors of 2 to 3 times the area strains in all subsequent stands. In the work of Maccagno et al. and Kemp, however, a mathematical rationale for the use of the constant factors was missing and modeling technique regarding the other thermo-mechanical parameters (strain rate and temperature evolution of the material), which is obviously critical for determining of the recrystallization behavior, was not given. But a mathematical rationale for the model[4,5] was missing. Lehnert and Cuong[6] proposed a model that calculates the strain and strain rate in rod rolling, based on assumption of plane state of deformation condition. The three-dimensional deformation zone is subdi vided into longitudinal strips of equal width to roll gap direction and each strip is analyzed separately. No experime ntal verification, however, was given to the assumption introduced in the formulation of the model. This approach might be applicable once the exit cross sectional shape at a pass can be predicted correctly.

In the mean time, Karhausen et al.[7] and Yanagimoto, et al.[8] presented three dimensional finite element analysis for the microstructure evolution in hot bar rolling, coupled with the laboratory scale experiment-based mircostructural evolution model. But considering computational time for the bar(or rod) mills which consists of a lot of number of passes and complicated mechanic al/thermal boundary conditions (the friction condition at the roll/material interface and heat transfer coefficients dependent on the temperature and contact pressure), the mathematical model with a simple form, which calculates the pass-by-pass plastic deformatio n(strain and strain rate) within very short time and the temperature evolution of material during rolling still remains as a useful tool.

Recently, Lee[9] proposed an analytical model, anchored in an elementary theory of plasticity, to calculate the pass-by-pass strain associated with oval-round(or round-oval) sequence most commonly employed in present bar (or rod) mills. The pass-by-pass strain was defined as maximum mean effective (equivalent) plastic strain at a pass. In the formulation of the model, assumed was homogeneous deform ation of workpiece during rolling. The validity of the analytical model[9] was examined by using a four-pass warm (650℃) plate and bar rolling experiment. It was verified by observing whether the mechanical behaviors of specimens obtained from the four-pass plate rolling experiment are consist ent with those acquired from the four-pass bar rolling experiment.[10]

This study presents a systematic procedure for computin g the thermo-mechanical parameter(strain, strain rate and temperature) necessary in the analysis of thermo-mechanic ally controlled rod(or bar) rolling process. A four-pass (oval-round or round-oval) bar rolling sequence was taken as an example. For comparison purpose, the strain was computed by using the area strain model[4,5] and the analytica l model[9] when the exit cross sectional shape and area of workpiece are obtained. The strain rate, defined as the strain over a time interval required for the workpiece to undergo this strain in the roll gap, is calculated. To calculate the temperature evolution of the material during rolling, solved was the equation of heat transfer problem, using implicit finite difference method.

Numerical simulation has been then performed for the four-pass bar rolling sequence using the thermo-mechanica l parameters as input to the recrystallization behavior and AGS evolution model being used in hot strip rolling. The AGS predicted at each pass was then compared with the ones obtained from the hot torsion experiment.

2. MODELING OF THERMO-MECHANICAL PARAMETERS

The following two sub-sections give the steps prerequis ites for the calculation of the thermo-mechanical parameter s (strain and strain rate per pass and temperature evolution of material during rolling). The model for calculating the strain and strain rate at a given pass is well described in Ref. [9~12] Thus, in what follows, a model for predicting the temperature evolution during rolling is explained.

2.1 Temperature evolution during rod(or bar) rolling

The thermal state of material during rod rolling depends on various factors such as rolling speed, initial temperature of the billet, plastic deformation of the workpiece, the cross sectional shape of workpiece at each pass, rolling condition in the individual passes and distribution of cooling and equalization zone(or line) between stands. To take care of these combined actions of these parameters, the model for the temperature evolution of workpiece(material) during rod rolling has been formulated based on the following assumptions:

i) Uniform initial temperature of the billet(or specimen)

ii) No longitudinal temperature gradient(i.e., infinitely long rod)

iii)Uniform heat generation across the cross section of workpiece due to plastic deformation in the roll gap

iv) Circular cross sectional shape at each pass

Assumptions i) and ii) are quite natural to treat this type of problem and assumption iii) is introduced because the strain was defined as maximum average effective (equivalen t) plastic strain at a given pass and the strain rate as the strain divided by the time required for the workpiece to undergo this strain in the roll gap. Finally, the background for assumption iv) is explained as follows.

The workpiece deformed at each pass is not of a circular cross sectional shape (even at round pass). Then, heat transfer problem that should be solved is a two-dimensional problem with a curved geometric boundary condition. At present, however, there is no systematic procedure for solving such problem using finite difference method. A way to overcome this difficulty may be employing the equivalent circle approximation method that transforms a non-circular cross sectional shape of workpiece into a circular one while net cross sectional area is maintained. The problem can be then reduced to the axi-symmetric heat transfer problem. This might seem an over-simplification but results will show it to be very fruitful in solving the heat transfer problem in rod (or bar) rolling. Under these assumptions, heat flow within the rod is governed by the following one-dimensional axi-symmetric heat transfer equation:

$$\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)+\dot{q}=\rho C_p\frac{\partial T}{\partial t}\ , \qquad (1)$$

where t is the time that takes for an element volume to travel the distance in the rolling direction. k, ρ and C_p are thermal conductivity, density and specific heat of the material, respectively. Note that $\dot{q}$ is the volumetric rate of heat generation within the rod due to the plastic deformatio n of the workpiece in the roll gap and can be expressed

$$\dot{q}=\chi\frac{\bar{\sigma}\dot{\bar{\varepsilon}}}{\rho\beta C_p}, \qquad (2)$$

where χ and β (=4.185kJ/kcal) are the faction of plastic deformation work converted into heat generation and the mechanical equivalent of heat, respectively. And $\bar{\sigma}$ repress ents the flow stress of the material (workpiece). Typically χ=0.9 is used.[1~4] The remained is stored in the material as energy associated with the defect structure. The flow stress of workpiece during rolling is a function of the strain, strain rate and temperature. The strain rate is again a functi on of the strain at a given pass. Therefore, the temperature increment due to the plastic deformation is mainly influence ed by the strain rate.

2.2 Experiment for the temperature model

The specimens were soaked in the furnace at the temperature of 1150℃ for 40 minutes. Because of the surface layers on the workpiece oxidized by air, the thermocouple system was employed to measure the thermal response of the workpiece during rolling. A thermocouple (type T) with 4.6mm diameter was embedded in 50mm deep holes drilled in the tail ends of the specimen as soon as it comes out from the furnace.

Experimental procedure and information regarding specime n size and the four-pass(round-oval or oval-round) rolling sequence are given in Ref.[10] Then, the workpiece with the thermocouple embedded was rolled into the round pass after it was rotated 90 degree in the length direction. Afterward, this procedure was repeated. In this way, the centerline temperature of material (during rolling and air cooling between passes) was monitored by a thermocouple connecte d to a chart recorder(YOKUGAWA, model: DX102).

3. NUMERICAL SIMULATION

Numerical simulations have been carried out using the recrystallization model and AGS evolution model being used in hot strip rolling, and the thermo-mechanical parameters as input data. The equations used in this study are listed in the Appendix. The thermo-mechanical parameters (strain, strain rate at a pass and temperature change of workpiece during rolling) have been obtained. It should be noted that the concept of metadynamic recrystallization introduced by Hodgson and Jonas[3,4] has nothing to do with this study. We just adopted their equations and used it as a tool to simulate recrystallization behavior and AGS evolution for the four-pass bar rolling sequence.[10]

The model calculating the thermo-mechanical paramete rs for rod(or bar) rolling is referred as thermo-mechanical model for convenience hereafter. This model is coupled with Shida's constitutive equation[20] when the flow stress of the material is calculated. The details of the parameters calculated are listed in Table 1 along with the inter-pass time and computed cross sectional area for each pass. The average temperature across the cross section of the specime n at the entry of each pass was taken as the representative temperature of the material during rolling. Finishing rolling speed was set up as 1.0m/sec.

In simulation, the thermo-mechanical model calculates the whole deformation parameters and temperature history of the material during rolling once the information regardin g the rolling schedule (roll groove geometry and inter-pass time), initial temperature and initial size of the material are given. This creates an output file for the whole process. The metallurgical model then picks up this file and compute recrystallization behavior and AGS evolution for the whole process using the material parameters.[4] This procedure is described in Fig. 1.

4. RESULTS and DISCUSSION

4.1 Deformation (strain and strain rate) parameters

Figures 2(a) and 6(b) show the strains and strain rates per pass calculated by the area strain model[4,5] and the analyt ical model.[9] The strains calculated by the area strain model show some fluctuation compared with the strains calculated by the analytical model[9]. This is because the area strain model does not consider the cross sectional shape change of workpiece and is purely associated with a constant factor which compensates the profile changes of workpiece in groove rolling, regardless of a pass type such as oval-round pass or round-oval pass. The strain calculated from the analytical model at the round pass(No. 2) are close to the area strain multiplied by 2.0 but those at the round pass(No. 4) approach to the area strains multiplied by 2.5. Meanwhil e those at the oval pass(No. 1 and 3) are middle of the area strains multiplied by 1.7 and 2.0. Similar pattern is observe d for pass-by-pass strain rates as shown in Fig. 2(b).

4-2. Temperature history of workpiece during rolling

Fig. 3(a) illustrates the centerline temperature history of material(workpiece) for the four-pass rolling sequence. Note the window time for the whole experiment is long since the pilot hot rolling mill does not have a capability of reversing the rolling direction. The difference between the measured and predicted value is seen to be poor, except at the very beginning stage. But this difference is not surprisi ng because it is attributed the assumptions introduced in the formulation of heat transfer equation in the specimen, i.e., no longitudinal(axial) temperature gradient. The ratio of the specimen length (150mm) to specimen diameter (28mm) is not large enough and furthermore the thermocouple is located only at 50mm deep in the tail ends of the specimen. Therefore, the measured cooling rate of centerline temperat ure should be faster than the predicted one. This makes the predicted temperature of the specimen greater than the mea sured one. The profile of temperature increment due to the plastic deformation for each pass is different. Especially, a very sharp increment of temperature is observed at the oval passes.

As can be seen in Eq (9), the temperature increment due to the plastic deformation might become higher as the rolling speed increases. Therefore, it is deduced that, at higher rolling speed, time-temperature history calculated by the area strain model[4,5] might be quite different from that computed by the thermo-mechanical model[9], if the heat transfer equation and solution method applied to the workpiece are the same.

4-3. Recrystallization behavior

Recrystallization behavior of workpiece during rolling has been simulated using the thermo-mechanical parameter s as input data for the recrystallization model being widely used in hot strip rolling. According to Maccagno et. al [4], the metadynamic recrystallization occurs during a given pass if the strain calculated at a given pass becomes greater than an critical strain

$$\varepsilon_c = 5.6 \times 10^{-4} d_0^{0.3} Z^{0.17}, \qquad (3)$$

where d_0 is initial grain size and Z is Zener-Hollomon parameter which is a function of the strain rate and temperature(See Appendix). It implies that the strain, strain rate and temperature at a pass affect recrystallization behavior significantly and it, in turn, influences the pass-by-pass AGS during rolling. Since the temperature varies across the cross-section, average temperature across the cross-section of the specimen was used when we simulate recrystallization behavior and AGS evolution.

The recrystallization behavior (static or metadynamic) at a given pass is determined by comparison of the calculate d strains and the critical strain. As shown in Fig. 4(b), for an example, static recrystallization takes place at pass No. 4 while metadynamic recrystallization occurs at pass No. 1,2 and 3, respectively. As a constant factor multiplied to the area strain increases, the number of passes where the calculated strains becomes larger than the critical strain increase. In Fig. 4(c) and (d), metadynamic recrystallization occurs at every pass. Note that Figs. 4(a) and 4(d) show a similar recrystallization behavior at all passes.

4-4 Evolution of austenite grain size (AGS)

Figure 5 illustrates the pass-by-pass AGS calculated and measured. To assure the credibility of experimental data, the torsion experiment was repeated three times under the same condition. For comparison, Table 2 shows the absolute values of the measured AGS and predicted one. The grain size was determined for all quenched specimens. A reticule of 5 parallel lines was used to measure the number of intercepts on 10 random fields. The total length of the lines was divided by the number of intersections, as described in ASTM standard E112.

When the predicted AGS is compared with the measured one, differences are noted at the pass No.1. After pass No.1, however, predicted AGS is in agreement with the measured one. Therefore, it is deduced that the proposed thermo-mechani cal model, coupled with the recrystallization behavior model and AGS evolution model, might be applied to rod(or bar) rolling directly.

Fig. 5 also shows that the AGS calculated from the thermo-mechanical model and the area strain model(area strain*2.5) agrees. It may imply that the area strain model multiplied by a constant factor of 2.5 might be used in the roughing train in rod mill, but this result is opposite to Maccagno's claim[4] that the constant factor of 1.7 should be used in the roughing trains. The big difference in AGS at pass No. 4 is attributed to that static recrystallization occur ed at the last pass when the area strain model*1.7 and 2.0 is used. This result confirm that the area strain model multipli ed by a constant factor dependent on a rolling speed lacks a mathematical rationale to be used as input to the recrystalli zation behavior model and AGS evolution model for the rod (or bar) rolling process. It should be stressed that the strain at a pass is merely a function of geometry (roll groove shape and exit cross sectional shape of a workpiece), but has nothi ng to do with the rolling speed.

Fig. 6 illustrates that the AGS decreased gradually up to approximately 18μm as the rolling went on. Most of the grains are shown to have an equi-axied shape even though the material have experienced severe deformat ion during rolling and the size of the grains less than 10μm are observed nearby the large size of the grains. From this, we can know that dynamic or metadynamic recrystallization was initiated in the material during rolling.

5. CONCLUSIONS

This study presents a systematic procedure for computin g the thermo-mechanical parameter (strain, strain rate and temperature) necessary in the analysis of thermo-mechanic ally controlled rod(or bar) rolling process.

Numerical simulation, predicting AGS for the four-pass bar rolling sequence and laboratory hot torsion experiment have been carried out to assess the potential for developing "Thermo-Mechanical Controlled

Process" technology in rod (or bar) rolling.

The conclusions are summarized as follows:

1) The thermo-mechanical parameters in rod (or bar) rolling should emerge naturally as outcomes of a model with a mathematical base otherwise the strain, strain rate and temperature needed to determine the recrystallization behavior (dynamic and/or static) may be calculated incorrect ly. This, in turn, guides us to predict a different recrystalliz ation behavior and affects significantly the prediction of AGS.

2) This present study demonstrated that, on an industrial scale, a quantitative description of the mechanica l and thermal state of the material during each stage of rod(or bar) manufacturing process, including controlled cooling system, will be possible if the mathemati cal model proposed in this paper can be mutually integrated with the recrystallization model and AGS evolution model being used in strip rolling, and a proper constitutive equation, describi ng the deformation behavior of the material at high strain rate (up to 3000 [1/sec]) and high temperature is available.

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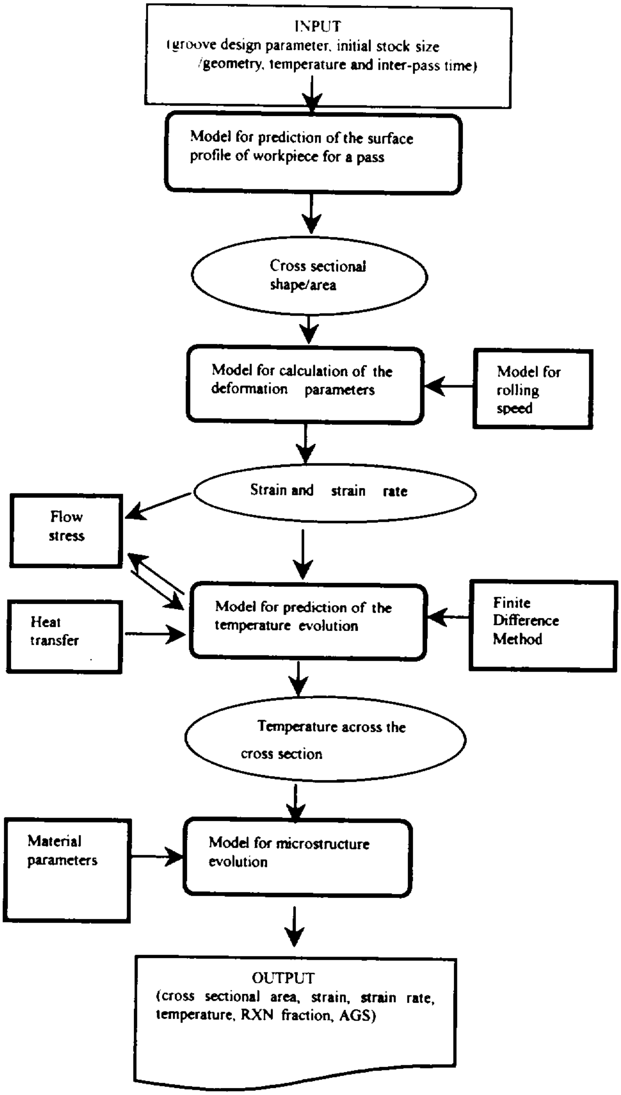

Fig. 1 Schematic of the thermo-mechanical controlled process model in rod (or bar) rolling proposed in this study

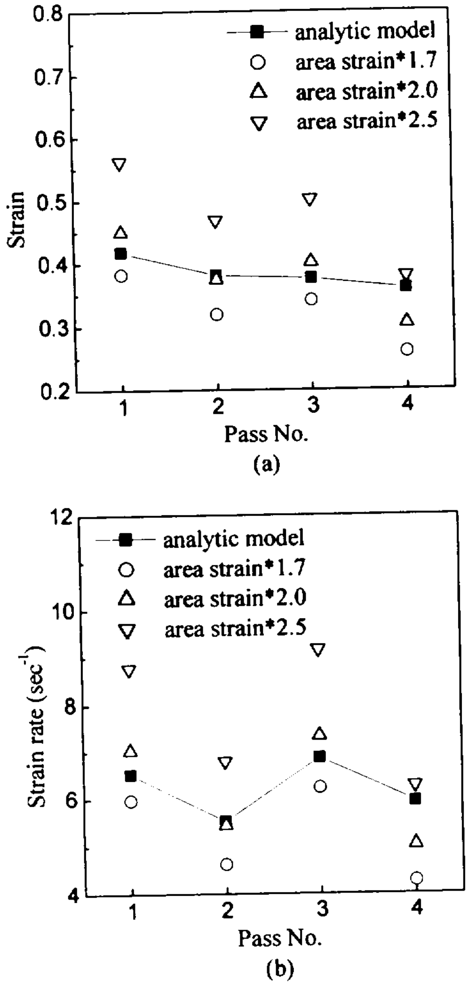

Fig. 2 Comparison of deformation parameters calculated by the analytic and area strain model when the finishing rolling speed is 1[m/s]. (a) Strains and (b) Strain rates

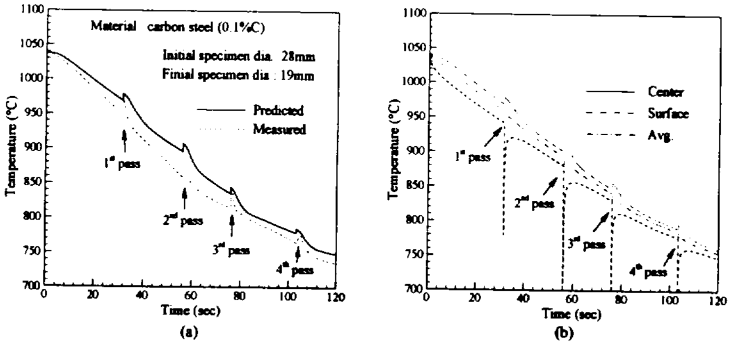

Fig. 3 Time - temperature history of workpiece during the four-pass bar rolling (a) Predicted and measured centerline temperature of specimen and (b) Predicted temperature across the cross section of specimen

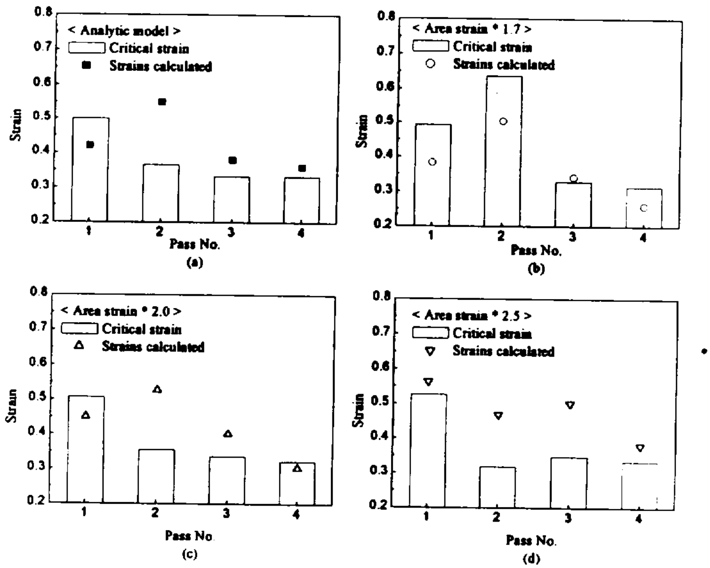

Fig. 4 Comparison of critical strains and strains calculated for the four-pass rolling sequence when the finishing rolling speed is 1[m/s].
(a) Analytical model and (b ~ d) Area strain model

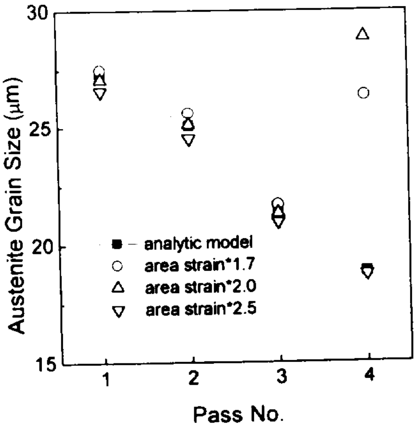

Fig. 5 Predicted AGS and measured one during

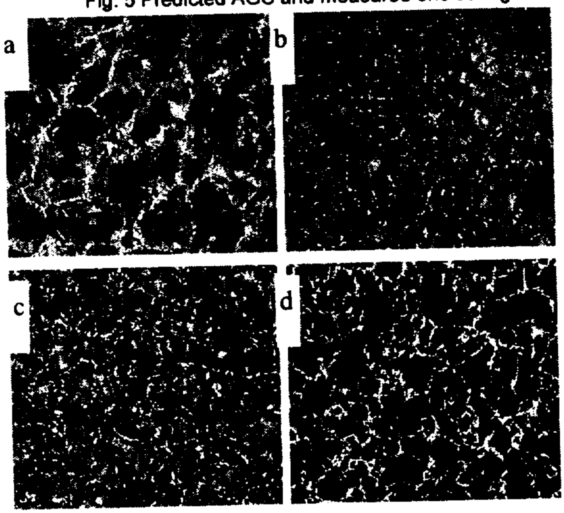

Fig. 6 The measured austenite grains for the four-pass bar rolling sequence. (a) 1st pass (b) 2nd pass (c) 3rd pass and (d) 4th pass.