Reverse Process Design Method Based on Recrystallization Models of CMn Steel

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A reverse process design method is established in this paper by reversely applying the Hodgson recrystallization models. The method allows a draft schedule to be designed according to the requirements of the resulting microstructure, and it is made up of the design equations of process parameters and the criteria-selected values of the parameters. First, the microstructural evolution is summarized as five paths, and the temperature and strain are set to fixed ranges according to the authors' experience. The mathematical models of the other parameters for each evolution path are established by applying the Hodgson recrystallization models. Secondly, criteria are established to select suitable values as a better draft schedule from uncountable groups of values. Finally, some examples are given and experiments are carried out according to the method. Metallographic observations showed that the final grain size was consistent with the design goals. The maximum relative error comparing the design goal was just 5.5%. These results prove that the method is sufficiently accurate and effective.


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1. Introduction

Microstructure has a significant influence on the mechanical properties of steel products. The achievements of Hall and Petch show that grain size is one of the main factors affecting the material properties and that small grains help improve the mechanical properties of materials. Therefore, grain refinement has become an effective way to improve material properties in modern steel production. To achieve this goal, structural property prediction and control (SPPC) is studied and applied extensively to predict microstructural evolution during the hot-working process.

The correlation between the parameters of the hot deformation processes and the resulting microstructure is the core of SPPC, and this correlation has been investigated extensively since the 1970s. The Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation was applied by Sellars et al. to describe the recrystallization kinetics. Although these researchers adopted the same equation for the volume fraction models, the coefficients and structures of these equations are different because the influences of process parameters on volume fraction were taken into consideration in different ways. Among these models, the models proposed by Hodgson and his co-workers are referred to extensively in fields related to the hot working of low-carbon steel and alloy steel because they are systematic and accurate in describing the resulting microstructure. Definement parameters and initial grain size are used to calculate volume fraction and grain size after deformation for dynamic recrystallization. Based on the results of dynamic recrystallization, models of metadynamic and static recrystallization were built with interpass parameters. Following complete recrystallization, grain sizes were described with subsection functions of time during grain growth.

Although the models mentioned above are applied extensively to forging parts and the hot rolling of bars, H-beams, wire rods, and plates, they are only adopted to predict the microstructural evolution rules during the manufacturing process. In some studies, the impact of the production process parameters on the microstructure is evaluated, and then the results of the study are applied to improve the properties of steel products through controlled rolling and cooling. However, these studies cannot actively meet the property requirements that are expected. According to current studies, properties can be described theoretically as a function of the microstructure parameters, and so a reverse process design method is established in this paper to solve this problem.

The grain size of austenite and the residual strain are known variables at the start of the method because they can be calculated by the relationships between the properties and them. Then, the relationship between the microstructure parameters and the process parameters are described clearly by the Hodgson models when the microstructural evolution paths are summarized on the basis of the recrystallization theories. Based on these relationships, the equations of the process parameters are established reversely. These equations confine the process parameters within their feasible regions. In order to obtain an available schedule from these feasible regions, a selection criterion of process parameters is proposed. Obviously, the requirements of the product microstructure can be actively satisfied by adopting this method during the process design stage. Moreover, one example is discussed in detail, for which corresponding verification experiments were carried out. Studies and experiments prove that by using this reverse process design method, it is possible to obtain the expected microstructure of steel products.

2. Classification of the Microstructural Evolution of Carbon Steel

Classification of the microstructural evolution must be finished before the reverse design process. Such classification is helpful for deducing the relevant equations because recrystallization for each evolution path is determinate. According to the recrystallization theories, the microstructural evolu-
tion of carbon steel can be summarized as five paths:

(I) \( X_{\text{DRX}} \geq 0.95 \),

(II) \( 0.95 > X_{\text{DRX}} \geq 0.05, X_{\text{MDRX}} \geq 0.95 \),

(III) \( 0.95 > X_{\text{DRX}} \geq 0.05, X_{\text{MDRX}} < 0.95 \),

(IV) \( 0.05 > X_{\text{DRX}}, X_{\text{SRX}} \geq 0.95 \), and

(V) \( 0.05 > X_{\text{DRX}}, X_{\text{SRX}} < 0.95 \).

where \( X_{\text{DRX}} \) is the volume fraction of dynamic recrystallization (DRX), \( X_{\text{MDRX}} \) is that of metadynamic recrystallization (MDRX), and \( X_{\text{SRX}} \) is that of static recrystallization (SRX).

To simplify the description, these five evolution paths are denoted as follows. For the first path, complete dynamic recrystallization occurs during deformation and grain growth occurs during the interpass time; this path is denoted as the PDG path. For the second path, incomplete dynamic recrystallization occurs during deformation. During the interpass time, complete metadynamic recrystallization occurs first and then grain growth occurs; this path is denoted as the PDMG path. As compared to the second path, the third path has no grain growth, and thus it is denoted as the PDM path. For the fourth path, no dynamic recrystallization occurs during deformation. During the interpass time, complete static recrystallization occurs first and then grain growth occurs; this path is denoted as the PNSG path. As compared to the fourth path, the fifth path has no grain growth, and thus it is denoted as the PNS path.

According to the equation of \( X_{\text{DRX}} \), the strain coefficient \( \lambda \) is defined to simplify the following deduction and description:

\[
\lambda = \frac{e}{\varepsilon_s} = 1 + 1.23 \sqrt{\frac{\ln(1 - X_{\text{DRX}})}{\ln 0.5}}
\]

\( \lambda \) equals 3.5571 when \( X_{\text{DRX}} \) equals 0.95 and it equals 1.3346 when \( X_{\text{DRX}} \) equals 0.05. That is:

- the PDG path corresponds to \( \lambda \geq 3.5571 \),
- the PDMG and PDM paths correspond to \( 3.5571 > \lambda \geq 1.3346 \), and
- the PNSG and PNS paths correspond to \( 1.3346 > \lambda \).

3. Establishment of the Design Equations for the Five Paths

In order to design a schedule reversely, the equations describing each parameter should be established first. There are five microstructural evolution paths according to the discussion above. The establishment of these equations for every path are discussed under the condition that the resulting microstructure is known. The austenite grain size \( (d, \mu m) \) and the residual strain \( (\varepsilon_r) \) are adopted to describe the resulting microstructure during this process.

There are six parameters that affect the resulting microstructure according to the recrystallization models. They are the initial grain size, strain, strain rate, interpass time, temperature during deformation, and temperature during the interpass time. However, these parameters cannot be solved independently during the reverse process because they couple with each other in the recrystallization models. Some parameters must be recognized as known variables to solve this problem. Temperature and strain were selected as the known variables with fixed ranges during the process because they can be easily controlled during the manufacturing. Therefore, the equations describing the initial grain size, the strain rate, and the interpass time are derived from Hodgson models. The following variables are used in this section:

- \( d_i \) is the minimum grain size under the current production limitations,
- \( T_G \) is the average temperature for the grain growth,
- \( T_D \) is the average temperature for the deformation,
- \( T_R \) is the average temperature for the metadynamic recrystallization or static recrystallization process,
- \( d_{mx} \) is the initial grain size before deformation,
- \( d_{dx} \) is the average grain size after incomplete recrystallization,
- \( d_{SRX} \) is the size after complete recrystallization,
- \( d_{MDRX} \) is the grain size after complete metadynamic recrystallization,
- \( d_{SRX} \) is the size after complete static recrystallization,
- \( X_s \) is the volume fraction of dynamic recrystallization,
- \( X_M \) is the volume fraction of metadynamic recrystallization,
- \( X_s \) is the volume fraction of static recrystallization,
- \( t_{0.5} \) is the time for 50% recrystallization,
- \( t_{ip} \) is the period time of the interpass process,
- \( t_{G} \) is the time of the grain growth process,
- \( \dot{\varepsilon} \) is the strain rate,
- \( \varepsilon_p \) is the peak strain at the peak stress,
- \( R \) is the gas constant,
- \( T \) is the absolute temperature, and
- \( Z \) is the Zener–Hollomon parameter.

3.1 Design equations of the PDG path

According to the discussions above, the models of DRX and grain growth are applied to establish the design equations of the PDG path. Temperature, strain, and the resulting microstructure are known variables during this process. The equations describing the initial grain size, the strain rate, and the interpass time of the PDG path are deduced in detail as follows:

Before the deduction, these constraints can be concluded according to the discussion above as

\[
d_i \leq d_{DRX} \leq d
\]

\( t_{ip} = t_G \) \hspace{1cm} (3)

\[
\varepsilon_r = 0
\]

Obviously, \( t_G \) should be solved to obtain the interpass time according to eq. (3). \( t_G \) can be derived from the equations of the grain size model for the grain growth. The equations in the Hodgson models are commonly expressed as

\[
d^m = d_{RX}^m + c_G \exp \left( \frac{-Q}{RT} \right)
\]

where \( Q \) is the apparent activation energy for grain growth, and \( m \) and \( c \) are constants that depend on recrystallization type and time, respectively. Their values are shown in Table 1. The time of the grain growth \( (t_G) \) can be derived as follows:
The strain rate can be derived from the equations for Z because the strain rate is only applied to calculate Z in the Hodgson models. Z should be solved first to obtain the strain rate. According to the Hodgson models, Z exists in the equations describing the grain size of DRX and the critical strain.9,10 If DRX is completed, the grain size is described as

\[ d_{\text{DRX}} = 1.6 \times 10^4 Z^{-0.23} \]  

(7)

According to eq. (7), Z is expressed as

\[ Z = \left( \frac{d_{\text{DRX}}}{1.6 \times 10^4} \right)^{-1/0.23} \]  

(8)

Z is also described as the following equation:9,10

\[ Z = \dot{\varepsilon} \exp \left( \frac{3.0 \times 10^3}{RT} \right) \]  

(9)

The strain rate can be derived from this equation. That is,

\[ \dot{\varepsilon} = Z \exp \left( \frac{3.0 \times 10^3}{RT} \right) \]  

(10)

The initial grain size can be derived from the equation calculating the critical strain. The critical strain is described as a function of Z and \( d_0 \) in the Hodgson models.9,10 That is,

\[ \varepsilon_c = 5.6 \times 10^{-4} d_0^{0.3} Z^{0.17} \]  

(11)

Moreover, \( \varepsilon_c \) equals \( \varepsilon / \lambda \) according to eq. (1). According to eq. (11), \( d_0 \) is expressed as

\[ d_0 = \lambda^{-1/3} \left( \frac{\varepsilon}{5.6 \times 10^{-4} Z^{0.17}} \right)^{1/0.3} \]  

(12)

where \( d_1 \) is an intermediate variable.

These equations can be used to adjust the process parameters after the relationship between the process parameters and the microstructure is established. In actual production, the temperature and strain of the work piece are chosen as fixed parameters because they are relatively easy to control. Then, the feasible region of \( t_G \) and Z can be obtained by using eq. (6) and eq. (8), respectively. The feasible region of \( t_p \) is also obtained according to eq. (3), and the feasible regions of \( \dot{\varepsilon} \) and \( d_0 \) can be obtained by substituting Z into eq. (10) and eq. (12), respectively. Therefore, reasonable process parameters meeting the criterion can be obtained. The other evolution paths follow a similar process, and thus they are not described here.

3.2 Design equations of the other paths

For the other paths, the deduction process is similar to that
of the PDG path, so those processes are omitted. However, the results for each path are listed in Table 2.

4. Criterion of Parameter Selection During the Design Process

Although the relationships between process parameters and microstructure have been suggested, there is a feasible region of each process parameter under the different evolution models. In theory, there are many combination schedules of process parameters that are able to achieve the purpose of controlling grain size. However, only a few of these schedules can be applied in a manufacturing process because the adjustment of process parameters is restricted. Therefore, a selection criterion of process parameters is proposed to obtain reasonable process parameters. The process parameters include different physical quantities, and their values vary greatly. In order to evaluate all parameters, a distance criterion is suggested. Because the reverse process design method is mainly oriented to an actual manufacturing process, the value of each parameter should fluctuate smoothly and lightly under the capacity of the relevant equipment. Taking into the above stations, the distance should be dimensionless as follows:

\[ s_i = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{b_i}{a_i} - 1 \right)^2 } \]  (31)

where \(a_i\) is the value of the \(i\)th parameter in the original process and \(b_i\) is the value of the \(i\)th parameter in a new process. Obviously, the smaller the distance, the less the original schedule is changed.

The following simplifications are adopted when the process parameters are designed without known values of the original process:

(a) Establish the boundaries of the temperature, the total strain, and the strain rate in the process on the basis of the capacity of the equipment.

(b) Establish the boundary of the grain size according to the established studies.

A set of available parameters can be obtained on the basis of this information. If the values in a set approach the final goals of the microstructure and properties, the values of the set are recognized as the original values of the process. Then, the above criterion can be applied by these measures.

5. Verification of the Design Equations

In order to verify the method suggested in the previous sections, an example of the PDG path is supplied in this section to illustrate the method. Some conditions are as follows:

(I) The resulting microstructure of a single pass of Q235 steel expected is \(d = 55 \mu m\) and \(\varepsilon_r = 0\).

(II) The temperature at the end of the hot working is 1000°C.

(III) The temperature drops with the increment of time during the whole process.

(IV) The maximum temperature deviation is less than 25°C.

(V) The austenite grain size ranges from 10 \(\mu m\) to 500 \(\mu m\) according to typical experience.

(VI) The total strain is less than 1 according to the capacity of a thermomechanical simulator (Gleeble-1500).

(VII) The strain rate is less than 30/s according to the capacity of a thermomechanical simulator (Gleeble-1500).

(VIII) The recrystallized volume fraction ranges from 0 to 1.

The feasible regions of process parameters in a single-pass deformation were obtained according to the results of the above discussion. Then, a group of process parameters was selected from the feasible regions according to the criterion. The values of the process parameters make up the schedule of a single-pass deformation. Finally, the schedules were carried out on the Gleeble-1500 and the grain size was measured.

5.1 Discussion of the PDG path

The interpass time of the PDG path equals \(t_0\) according to eq. (3). The feasible region of \(t_0\) for the three paths was obtained and is shown in Fig. 1. For the PDG and PDMG paths, the upper boundary was obtained according to eq. (6) when \(d_{RX}\) equaled 10 \(\mu m\). The lower boundary is the line at which \(t_0\) equals zero when \(d_{RX}\) equals 55 \(\mu m\). Moreover, the left and the right boundaries are determined by the range of temperatures. The feasible region of \(t_0\) for the PDG and PDMG paths was determined by the four boundaries. As can be seen in Fig. 1, \(t_0\) decreases with increasing temperature when \(d_{RX}\) is a fixed constant. The feasible region of \(t_0\) for the PNSG path was established similarly. Obviously, the feasible region for the PNSG path was smaller than that of the PDG path under the same conditions. That made the PNSG path more difficult to carry out than the PDG and PDMG paths.

The feasible region of the strain rate for the PDG path was established and is shown in Fig. 2. The upper boundary was obtained with eq. (10) when \(d_{RX}\) equaled 10 \(\mu m\). The upper boundary is replaced when the line strain rate equals 30/s according to the seventh condition above if the strain rate is bigger than 30/s. The lower boundary is obtained when \(d_{RX}\) equals 55 \(\mu m\). Similarly, the left and right boundaries are determined by the range of temperatures. The feasible region of the strain rate was thus determined by these four boundaries. As can be seen in Fig. 2, the strain rate increased with increasing temperature when \(d_{RX}\) was a fixed constant.

The feasible region of the initial grain size for the PDG path was decided by the initial grain size coefficient (IGSC) and the equation of \(d_j\) according to the eq. (12). The IGSC
The curve is shown in Fig. 3(a). It decreases rapidly with increasing $\lambda$ and the maximum is 0.0146 at $\lambda = 3.5571$ within the PDG path. The feasible region of $d_1$ is shown in Fig. 3(b). The upper boundary is obtained when $d_R$ equals 55 $\mu$m. The lower boundary is obtained when $d_R$ equals 10 $\mu$m. As can be seen in Fig. 2, $d_1$ increased with increasing strain when $d_R$ was a fixed constant. The feasible region of $d_0$ is similar to that of $d_1$ when $\lambda$ is a fixed constant. However, the lower boundary should adopt the line $d_0$ equals 10 $\mu$m if $d_0$ is smaller than 10 $\mu$m.

Similarly, the other paths could be discussed by using their equations, and the feasible regions of the process parameters were obtained. To simplify the design of the experiment, the initial grain size for each path was given as approximately 115 $\mu$m. Simultaneously, the total strain was the same as that given above, 55 $\mu$m. According to the above discussion, the parameters selected from the feasible regions for the PDG, PDMG, and PNSG paths are shown in Table 3. However, the parameters of PNSG in Table 3 were not effective because the strain rate was beyond the capacity of the machine. This proves that it is more difficult to create the same microstructure under the same conditions using the PNSG path than it is using the other two paths. This path was therefore ignored in the verification experiments.

### 5.2 Verification experiments and analysis

A couple of single-pass compression tests were carried out on a Gleeble-1500 machine. The schedule of the tests was designed according to the data in Table 3 and that given by Qingqiang.\(^{20}\) The standard samples were three ø8 × 15 Q235 cylinders. The main chemical elements of the steel are shown in Table 4. They were heated to 1300°C and then held at this temperature for 3 min. One of the samples was quenched to investigate the initial state of the samples. The other two were cooled to 1020°C and then compressed at a fixed strain rate. The samples were held for a period of time according to the value of $t_p$. They were also quenched at the end of the inter-pass time. Metallographic observation was carried out after the experiment to obtain the final grain size of the austenite. The experimental results are shown in Fig. 4. The initial state of the austenite grains is shown in Fig. 4(a). The average value of $d_0$ was approximately 115 $\mu$m at the end of the heating process. The relative error was 1.7% for the PDG path and 2.4% for the PDMG path. The states of the austenite grains after deformation are shown in Fig. 4(b) and Fig. 10(c) for the PDG and PDMG paths, respectively. The average value of

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**Table 3** Process parameters of a single pass deformation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Grain growth type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>°C</td>
<td>1000 1000 1000</td>
</tr>
<tr>
<td>$d$</td>
<td>$\mu$m</td>
<td>55 55 55</td>
</tr>
<tr>
<td>$e_r$</td>
<td></td>
<td>1 0 0</td>
</tr>
<tr>
<td>$T_G$</td>
<td>°C</td>
<td>1010 1010 1010</td>
</tr>
<tr>
<td>$t_G$</td>
<td>s</td>
<td>30 30 14</td>
</tr>
<tr>
<td>$T_R$</td>
<td>°C</td>
<td>- 1015 1015</td>
</tr>
<tr>
<td>$T_D$</td>
<td>°C</td>
<td>1020 1020 1020</td>
</tr>
<tr>
<td>$X_D$</td>
<td></td>
<td>1 0.95 0.9344</td>
</tr>
<tr>
<td>$X_M$</td>
<td></td>
<td>1 - 0.95</td>
</tr>
<tr>
<td>$X_S$</td>
<td></td>
<td>1 - 0.95</td>
</tr>
<tr>
<td>$\lambda$</td>
<td></td>
<td>1 3.5571 2.4905</td>
</tr>
<tr>
<td>$e$</td>
<td></td>
<td>1 0.55 0.55</td>
</tr>
<tr>
<td>$t_p$</td>
<td>s</td>
<td>30.0 33.0 15.2</td>
</tr>
<tr>
<td>$\dot{e}$</td>
<td>1/s</td>
<td>0.0413 0.3408 71.1910</td>
</tr>
<tr>
<td>$d_0$</td>
<td>$\mu$m</td>
<td>113.1 112.2 113.9</td>
</tr>
</tbody>
</table>

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**Table 4** Mass fraction of main chemical elements of Q235B steel.

<table>
<thead>
<tr>
<th>chemical element</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass fraction (%)</td>
<td>0.2</td>
<td>0.3</td>
<td>0.198</td>
<td>0.22</td>
<td>0.015</td>
<td>0.005</td>
<td>0.007</td>
<td>0.002</td>
<td>0.0133</td>
</tr>
</tbody>
</table>
was approximately 52 μm at the end of the PDG path and 57 μm at the end of the PDMG path. The relative error was 5.5% for the PDG path and 3.6% for the PDMG path. The parameters of the PDG and PDMG paths in Table 2 reached the target microstructure with little error. That proves that the method adopted above is effective.

6. Conclusions

According to the analysis above, the following conclusions can be drawn:

(1) The microstructural evolution of carbon steel is summarized as five paths according to the recrystallization theories. The reverse design equation of each path was established by applying Hodgson models under the conditions that the grain size and residual strain at the end of an evolution path are known. The equations defined clearly the feasible regions of all parameters. The values contained in the feasible regions allowed for the construction of innumerable schedules. This work makes the reverse design of schedules available. In order to obtain a couple of schedules, criteria were proposed to evaluate the values selected from the feasible regions of the process parameters. This made the schedules obtained by the design equations limitable and available. Moreover, the reverse design method was established completely by combining the reverse design equations with these criteria.

(2) Three universal paths were illustrated with the method when the grain size at the end of each path was 55 μm. During this process, the temperature ranged from 1000°C to 1025°C and the strain ranged from 0 to 1. The feasible regions of the interpass time, the strain, and the initial grain size were established and are discussed in detail for each path. The results revealed that the PNSG path was more difficult to carry out than the other two paths under the same conditions. A schedule was obtained for both the PDG path and the PDMG path.

(3) The PDG and PDMG paths were verified with their schedules on a Gleeble-1500 machine. Metallographic observations were carried out after the experiments. The results showed that the final grain sizes were 52 μm and 57 μm for the PDG path and the PDMG path, respectively. The relative error of grain size between the test value and the design goal was 5.5% for the PDG path and 3.6% for the PDMG path, which proves that the method proposed in this paper is accurate and effective.

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