Original Article

Optimization of TMCP strategy for microstructure refinement and flow-productivity characteristics enhancement of low carbon steel

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ABSTRACT

Improving the mechanical properties of low carbon steel through the microstructural refinement without adding alloying elements is a complicated scientific and technical mission. This challenge can be overcome by using thermo-mechanical controlled processing (TMCP) technology. Most researches have examined the influence of TMCP on the microstructure development without shed light on the flow characteristics. The current work aims at studying the effect of applying different TMCP strategies on the microstructure refinement, flow-productivity characteristics, i.e. peak stress, flow stress, strain hardening index, Zener–Hollomon parameter and total strategy time, of low carbon steel. These TMCP strategies involve applying heavy deformation in single-pass TMCP strategy versus light deformation/pass in multi-pass TMCP strategy through applying different plane-strain hot compression regimes using Gleeble 3500 thermo-mechanical simulator. The proposed TMCP strategies have been involved application of heavy accumulative strain of 45–57% through: (1) single pass TMCP strategy at various strain rates (0.01, 0.1 and 1.0 s\(^{-1}\)), (2) double pass TMCP strategy at different strain rates and (3) multi-pass TMCP strategy at strain rate of 0.1 s\(^{-1}\). Microstructures after the diverse TMCP strategies reveal ferrite grain refinement and the flow curves show typical strain hardening. This denotes that the working grain refinement mechanism during all TMCP is dynamic strain-induced transformation of austenite to ferrite. It has been found that the strain rate plays a considerable role in determining the flow characteristics regardless the applied TMCP strategy type. Double-pass TMCP strategy is the optimum TMCP strategy that promotes the ferrite refinement and enhances the flow and productivity characteristics.

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1. Introduction

Grain refinement of metallic materials gives rise to a significant improvement in both toughness and strength without the need of adding expensive alloying elements [1]. In spite
of the huge efforts and attempts, the generation of ultra-fine ferrite (UFF) grain structure in low carbon steel without alloying elements addition is still a complex mission. In low carbon steel manufacturing, the thermo-mechanical controlled processing (TMCP) has been developed as a grain refinement method that can fulfill a remarkable simultaneous upgrading in productivity and service performance [1,2]. TMCP involves controlling the hot rolling regime and the subsequent cooling [3–5]. The limiting factors for wide spreading of the conventional TMCP are the high rolling capacity and high power exhaustion required. Thus, in order to treat the accompanied constraints to the traditional TMCP, novel TMCP routes have to be developed to diminish the rolling capacity and enhance the productivity [2,3]. It is noteworthy that TMCP has been attracted research in order to widen the industrial application of low cost-low carbon steel in the absence of any alloying additions [1,2,4,6–10].

Previous authors had developed a new and simple type of TMCP on a martensite starting microstructure to produce UFF low-carbon steels, this method is characterized by traditional 50–70% cold-rolling and annealing of a martensite starting microstructure [11–13]. This thermomechanical technique can replace severe plastic deformation processes which are difficult to apply to practical manufacturing, because of their complicated procedures and inapplicability to bulky workpieces [11]. This approach is believed to be superior for mass production of UFF steels [13].

Ueji et al. [11] applied this way to plain low-carbon steel sheets. At first, the sheets were austenitized at 1000 °C for 1800 s in Argon plus 10vol% H2 atmosphere, followed by water-quenching to get the martensite structure. Then, these sheets with martensitic microstructure were cold-rolled by 50% reduction in thickness in three passes with subsequent annealing for 1800 s at various temperatures ranging from 200 to 700 °C. After the 50% cold rolling, they observed formation of ultrafine inhomogeneous microstructures. These microstructures had three shapes of morphologies: ultrafine lamella dislocation cell irregularly bent lath and kinked lath. After annealing, the microstructures revealed multiphase ultrafine structure composed of equiaxed ultrafine ferrite grains, uniformly distributed nano-carbides and small blocks of tempered martensite.

Najafi et al. [12] demonstrated the mechanisms responsible for the formation of ultrafine grained microstructure in low-carbon steel during tempering of 70% cold-rolled martensite, accomplished in seven rolling passes, at temperature range (300–600 °C). They stated that four different stages were distinguished during process using microstructural evolution. Firstly, in Stage I, the precipitation of carbides and dislocation recovery took place. In Stage II, the extended recovery mechanism was suggested for the observed microstructural coarsening. Finally, in Stages III and IV, a continuous recrystallization process was proposed based on the microstructural evolution.

Lan et al. [13] also obtained ultrafine ferrite grains by tempering of 50% cold-rolled martensite in a low carbon steel for 3600 s at the temperature range from 500 to 600 °C. They stated that multilevel subdivision mechanisms are the responsible for the formation of ultrafine ferrite grains in cold-rolled martensite. Firstly, subdivision of a prior austenite grain into several martensite packets by phase transformation were observed and then further subdividing the martensite structure into ultrafine cell blocks by plastic deformation. They observed a relatively large disorientation between the ultrafine cell blocks at a moderate strain level in martensite due to the interaction between the transformations and the developed dislocations during deformation. During tempering, sharp grain boundaries were developed from cloudy cell block walls as a result of dislocation rearrangement and annihilation and the ultrafine ferrite grains were developed from these cell blocks during tempering.

Since cold rolling of full martensite structure requires high rolling load, in addition to the possibility of formation of transverse cracking at the edge of the sheet metal [14]. Therefore, a modified TMCP was released for low carbon steel which involved heavy cold working (>40%) on a dual phase ferrite-martensite starting microstructure, obtained from previous intercritical annealing, followed by annealing of this cold rolled dual-phase structure and subsequent water quenching to produce ultrafine grained dual phase structure [14–17].

Alizamini et al. [14] developed ultra-fine grained dual phase structures in a plain low carbon steel. They studied the effect of thermo-mechanical processing parameters, i.e. heating rate to the intercritical temperature, on the microstructure and mechanical properties. They stated that rapid heating and cooling cycle, to and from the intercritical annealing temperature, respectively, is essential to guarantee formation of ultra-fine grain dual phase structures with optimum properties. Fundamentally, this requirement is to avoid the undesired growth of ferrite and austenite grains that further result in a coarser ferrite martensite structure.

Karmakar et al. [15] studied the effect of heating rates to the annealing temperature with intermediately water quenched for dual phase cold-rolled specimens on the evolved microstructure. They found that high heating rate to the annealing temperature resulted in finer ferrite grain structure which increased the tensile strength by ~200–250 MPa and enhanced the ductility by ~2–6%. They reported that fine ferrite grain size can be also obtained even after slow annealing and quenching of cold-rolled sheets but at the expense of formation of high amount of martensite (>40%), which is detrimental to ductility. Therefore, rapid annealing and quenching of cold-rolled steels is more suitable from this respect.

Mirzadeh et al. [16] produced different ferritic-martensitic dual phase structures, i.e. different size, morphology, and distribution of martensite, in low-carbon steel by altering the initial microstructures using heat treatment and thermo-mechanical processing routes. They concluded that the strength, ductility and work-hardening rate of dual phase steel depend on the volume fraction of martensite and on the attributes of the martensite constituent. They stated that fine-grained dual phase steel can be developed by intercritical annealing of ultra-fine dual phase structure which can be produced by cold rolling followed by tempering of a martensite starting microstructure. This fine-grained dual phase steel showed an excellent combination of strength and ductility mainly as a result of the excellent work-hardening behavior. They concluded that the microstructure refinement is a better approach to enhance the mechanical properties compared with increasing the volume fraction of martensite.
Jamei et al. [17] studied the effect of the intercritical annealing time on the microstructure and tensile properties of low carbon steel. Long-term intercritical annealing resulted in the appearance of the yield-point elongation in the tensile stress–strain curves, which was related to the enrichment of austenite with manganese. The enrichment of austenite with manganese also resulted in the decrease of the martensite start temperature which is known to be responsible for the decrease in the volume change of austenite to martensite transformation. They found that refining the pre-intercritical annealing microstructure results in finer duplex dual phase microstructure, which promotes the tensile properties and work-hardening behavior.

The most novel approach of achieving grain refinement through TMCP of low carbon steel is the formation of ultra-fine ferrite (UFF) microstructure through the austenite transformation to ferrite within or subsequent to the plastic deformation of austenite [1,3–5,10]. During TMCP, many possible refining mechanisms may work, encompass recrystallization of austenite and/or ferrite and deformation-induced transformation, depending on the deformation temperature and amount of deformation [2,3,5,10]. These mechanisms may work either individually, simultaneously or interactively and lead to dynamic softening that dominant at elevated temperature and minimal strain rate due to raising the ability of grain boundary movement and extending the allowable period for nucleation and growth of the dynamically recrystallized grains at these processing conditions [7,10].

Heping et al. [7] studied TMCP behavior and the microstructural evaluation of low carbon steel in the temperature extent from 750 °C to 900 °C and in the strain rate extent from 0.001 s⁻¹ to 1 s⁻¹ during compression at elevated temperature. They found that with raising deformation temperature and diminishing strain rate, the grain size and the amount of the recrystallized ferrite grains rise while the flow stress decreases. In their work, the flow curves exhibit work hardening zone with subsequent dynamic softening as a result of recovery/recrystallization.

Ohmori et al. [1] studied the effect of a severe worm deformation in the temperature extent from 500 °C to 650 °C and a strain rate of 1 s⁻¹ or 0.01 s⁻¹ on the grain refinement of low carbon steel during applying high amount of deformation in one pass. They found that the domain refining mechanism is a continuous recrystallization and that the creation of UFF grains is promoted by lowering the Zener–Hollomon (Z–H) parameter.

Sun et al. [10] examined the influence of multi-pass hot deformation and the dynamic recrystallization of ferrite on the tensile properties of a low carbon steel. They found that formation of a fine structure can be accomplished through a precise dominating the influence of the deformation-enhanced transformation on the dynamic recrystallization of ferrite and vice. They observed also that the strength of a 0.2% carbon steel can be multiplied with a small dropping in the tensile ductility by evolution of a ferrite grain size of 3–5 μm. Sun et al. [10] also stated that with appropriate control of production technology, the fine structure is attainable and the flow characteristics of low carbon steel can be enhanced and optimized.

Other TMCP refinement mechanism involves maximizing the amount of nucleation positions per unit volume in the un-recrystallized austenite phase which then transform to a fine ferrite structure [4,18]. This type of refinement mechanism is known as dynamic strain-induced transformation (DSIT). The expression “dynamic” refers to the dynamic behavior of austenite to ferrite transformation within austenite deformation [2–4,18]. This dynamic behavior can be asserted by monitoring the flow behavior and the formed ferrite grains. DSIT mechanism is a new hopeful and favorable processing technique for ferrite grain refinement [4]. DSIT may lead to dynamic softening or work hardening relying on a deformation temperature and a strain rate. The work hardening is prevailing at depressed temperature and high strain rate in contrast to dynamic softening [18].

Gong et al. [3] investigated the influence of TMCP route on a creation of ultrafine grains in low carbon micro-alloyed steels. They found that the amount of the formed ferrite due to DSIT raised with the rising the strain and the isothermal holding after deformation. They also stated that DSIT is an efficient method to refine the final microstructure and it is accompanied with diminishing the deformation load and promoting the productivity.

Zhuang et al. [2] studied the microstructure and mechanical properties of low carbon steel under different processing and cooling parameters. They stated that the austenite cannot be recrystallized or only partially recrystallized within or after deformation at relatively low deformation temperature and short inter-pass time which induced the deformation induced ferrite transformation (DIFT). They found that the mechanical properties are considerably upgraded by applying TMCP at low temperature and fast cooling rate due grain refinement.

Sun et al. [18] investigated the influence of strain path on DSIT in a micro-alloyed steel using two and eight passes hot cyclic torsion at temperature extent among the Ae₃ and Ar₃ of the steel to a total accumulative strain of 2.0. They observed work hardening and a peak flow stress at a strain of 0.8 during the forward torsion of 2-pass test, followed by a slight dynamic softening accompanied with a slight reduction in the flow stress in the second pass. They also stated that DSIT might occur at temperatures higher than the austenite to ferrite transformation temperature (Ae₃), as a result of rising the Ae₃ temperature for the deformed austenite by means of diminishing the energy hindrance for nucleation and enhancing the driving force for austenite to ferrite transformation.

Most research had been focused on the effects of deformation temperature, accumulative strain, strain rate and cooling rate on the creation of UFF grains in steel alloys [1–10,18,19], in order to evolve new environmental beneficial high-performance steels. In the industrial rolling mill, the implementation of heavy deformation in a single-pass at a low temperature, with fast cooling rate, represent enormous challenge for executing DSIT in industry to manufacture UFF steels due to the requirement of excessive rolling load to overcome the high flow stress that surpasses the capacity of available hot rolling mills [6,10,18]. To solve this problem, practical industrial approaches have to divide this heavy single-pass deformation to multi-pass deformations to diminish the required rolling capacity; where the amount of deformation/pass does not exceed the allowable limit of
Fig. 1 – The designed TMCP strategies.
the industrial practice [10]. Subsequently, it is important to acquire an essential understanding of the effect of the different rolling regimes on the microstructure and flow characteristics developed through DSIT during TMCP.

The current study deals with TMCP from a different perspective which is more appropriate to the industrial practice. During the designing of the proposed TMCP strategies, DSIT is the targeted refining mechanism, with full avoidance of any recovery and recrystallization operations in order to enhance the strain hardening during deformation and bypassing any softening behavior. In addition to that, the productivity of the TMCP strategy has taken into consideration through reducing the required rolling load (flow stress) and the processing time on the production line. Therefore, this work aims at attaining the optimized TMCP strategy to achieve the best performance and productivity for low carbon steel; one of the lowest cost applied material in automotive and structural applications. The effect of TMCP strategies including: number of passes (single-pass, double-pass, as well as multi-pass deformation) and strain rate (0.01, 0.1 and 1 s\(^{-1}\)) on the average grain size and flow-productivity characteristics, i.e. peak stress, flow stress, strain hardening index, Zener--Hollomon (Z-H) parameter and total strategy time, had been studied through performing different hot compression regimes using a thermo-mechanical simulator (Gleeble 3500), keeping the total accumulative stain in a range (45–57%).

2. Experimental procedure

Different TMCP strategies have been performed on specimens of low carbon steel utilizing a thermo-mechanical simulator (Gleeble 3500). Table 1 presents the chemical composition of the studied steel alloy. As-received material was hot-rolled plates, with thickness of 15 mm, supplied by the Egyptian iron and steel company-Helwan, Egypt. Specimens for thermo-mechanical simulator were machined from these plates as bars of 10 mm diameter and 116.5 mm length, threaded from both ends by M10. Each specimen was then welded to the thermocouple by using thermocouple welder device and then fixed between two jaws of copper in the thermo-mechanical simulator.

At first, heating-cooling cycle, without deformation, was carried out to detect the critical transformation temperatures by dilatation using the thermo-mechanical simulator, through heating the specimen to 900 °C in 15 min. from room temperature, holding for 20 s to eliminate thermal gradients then cooling down to room temperature in 5 min. During this cycle, the temperatures were recorded against the change in length of the specimen (dilation). Dilation test had been revealed that the first critical temperature (\(A_C\)) was 818 °C and the second critical temperature (\(A_C\)) was 868 °C.

The proposed TMCP strategies involve applying different plane-strain hot compression regimes. All strategies have been designed on the basis of taking the industrial requirements into consideration, i.e. reducing the processing time on the production line. Single-pass (SP), double-pass (DP) and multi-pass (MP) TMCP strategies have been applied at various strain rates, keeping the total amount of deformation in the range of 45–57%. Relatively low heating rate of 1.33 °C/s up to 1000 °C for all strategies has been undertaken to ensure obtaining a homogeneous structure before deformation. All strategies have been started at high processing temperature in austenite range (1000 °C) and soaking for 10 sec to diminish the required flow stress and reduce the soaking time that may reduce the processing cost when applied for industrial scale. High cooling rate of 46 °C/s to room temperature after deformation has been undertaken in all TMCP strategies to prevent the coarsening of ferrite grains and to preserve the deformed microstructures.

Schematic of a typical single-pass (SP) TMCP strategy is shown in Fig. 1(a). After soaking specimens for 10 sec at 1000 °C, 45% reduction was applied in one pass at different strain rates of 0.01, 0.1 and 1 s\(^{-1}\). A schematic presentation of the double-pass (DP) TMCP strategy is shown in Fig. 1(b). At first, the specimens were soaked for 10 s at 1000 °C followed by applying 28% reduction in the first pass. The second pass involved cooling the specimens to 900 °C with an inter-pass time of 10 s and applying 25% reduction. This strategy was repeated using different strain rates (0.01–0.1–1 s\(^{-1}\)). Fig. 1(c) demonstrates a schematic presentation of multi-pass (MP) TMCP strategy. This strategy had been involved applying of four passes of hot compression at a constant strain rate 0.1 s\(^{-1}\). Each deformation pass was executed for a definite strain and definite temperature. Deformation was performed at a temperature extent of 1000–850 °C with subsequent cooling to room temperature. The amount of deformation/pass and the inter-pass time are shown in Fig. 1(c). This strategy is nearly similar to the actually applied in the steel sheet production line of Egyptian iron and steel company-Helwan. The first (1000 °C–16% deformation) and second (950 °C–16% deformation) passes are acting as the roughing stage followed by the third (900 °C–14% deformation) and fourth (850 °C–11% deformation).

| Table 1 – Chemical composition of the studied hot rolled low carbon steel alloy (wt.%) |
|-----------------|---------|--------|-----|-----|------|-----|
| C               | Si      | Mn     | P   | S   | Al   | Fe  |
| 0.06            | 0.04    | 0.03   | 0.04| 0.04| 0.08 | Balance |

Fig. 2 – Optical micrograph of the as-received microstructure of the hot rolled low-carbon steel plate.
Fig. 3 – Optical micrographs after different TMCP strategies.

deformation) passes representing the finishing stage of the rolling process. A delay time, of 20s between the 2nd and 3rd pass, was involved to simulate the required duration for transferring the rough rolled plate to the finish rolling stands.

These specimens were then sectioned perpendicular to the compression axis for microstructural analysis. All specimens have been prepared for metallographic investigation. The metallographic procedure involved grinding, polishing and etching with 2% Nital. These prepared specimens were photographed and investigated using optical microscope and scanning electron microscope (SEM). The average grain size was estimated using image analyzer and the average of twenty readings was recorded.

3. Results and discussion

3.1. Effect of TMCP strategy on microstructure

Fig. 2 demonstrates the microstructure of the as-received hot rolled low carbon steel plate. The microstructure
constitutes ferrite and pearlite phases with an average grain size of 12.1 μm. Fig. 3 displays optical micrographs after the different TMCP strategies. All TMCP strategies reveal the same ferrite and pearlite structural phases with different fraction, morphologies and sizes.

At low strain rate of 0.01 s⁻¹, the microstructure exhibits slightly elongated grains of ferrite and pearlite. However, by increasing the strain rate regardless the type TMCP applied strategy, the microstructure reveals finer equiaxed ferrite and pearlite structure.

As a result of the large accumulative strain in each TMCP strategy, high amount of stored energy is generated in the materials. This stored energy enhances the driving force for the dynamic austenite to ferrite transformation during deformation [20]. There is no recrystallization neither for austenite nor ferrite. This indicates that at certain deformation temperature around or above A_c3, and with sufficient accumulation of deformation, DSIT leads to grain refining. Therefore, in all TMCP strategies, the working grain refinement mechanism is only DSIT. Dong and Sun [4] reviewed the scientific advancement in the theory and implementation of DIFT and stated that at a relatively low deformation temperature, above austenite to ferrite transformation temperature, and short inter-pass time, the deformed austenite would not recrystallize or only partially recrystallize, and DSIT can proceed.

Fig. 4 shows low and high magnifications SEM micrographs after the different TMCP strategies at strain rate of 0.1 s⁻¹. All micrographs reveal a ferrite-pearlite structure with ferritic matrix. At higher magnification of 30000×, pearlite morphology can be distinguished. The average grain size after each TMCP strategies, at a strain rate of 0.1 s⁻¹, is displayed in Fig. 5. The average grain size decreases by 40.5%, 47.1% and 43% after SP, DP and MP strategies, respectively, as compared with the as-received average grain size. The finest structure was obtained after DP strategies while the coarsest structure was obtained after SP strategies. MP TMCP strategy exhibits
an intermediate value of average grain size. Turning from SP to DP TMCP strategies, the average grain size decreases from about 7.2 μm to 6.4 μm while estimated to be 6.9 μm after MP TMCP strategy.

The coarsest average grain size formed after SP TMCP strategy may be due to applying a heavy amount of deformation in short time, at constant strain rate of 0.1 s⁻¹, which in turn does not give enough time for the atomic diffusion during DSIT.

Sun et al. [18] observed that strain path with numerous reversals and small strain amplitude in each pass leads to suppression of DSIT of a micro-alloyed steel as compared to the extended DSIT ferrite resulted from a strain path with a single reversal and large strain amplitude in each pass. They stated that the amount of deformation/pass, not the total accumulative strain, locates the possibility of DSIT to take place, depending on the threshold strain for the beginning of DSIT. Dong and Sun [4] observed that decreasing the deformation temperature enhances DSIT and refines the ferrite grain size at a temperature above the critical transformation temperature of austenite to ferrite. They mentioned also that DSIT will be frustrated at temperatures lower than the critical transformation temperature of austenite to ferrite because of a preferential formation of pro-eutectoid ferrite. These observations interpret the higher average grain size obtained, in the current work, after MP TMCP strategy as compared to DP TMCP strategy, where the final (fourth) pass of MP TMCP strategy is below the critical transformation temperature of austenite to ferrite of the studied alloy.

3.2. Effect of TMCP strategy on flow-productivity characteristics

3.2.1. TMCP strategy vs. flow behavior

Figs. 6 and 7 present flow stress–strain curves of the specimens during the physical simulation of the different TMCP strategies. Continuous work hardening had been observed in all passes of the different TMCP strategies without any softening; hence the deformation proceeds without any dynamic recovery and recrystallization. This is another evidence, with the evolved microstructure, that the working grain refinement mechanism during the undertaken TMCP strategies is only DSIT.

There is an insignificant change in the initial flow stresses of the first pass in all TMCP strategies. Whereas the flow stress increases with number of passes in DP and MP TMCP strategies at all strain rates. This is due to the work hardening occur in the previous pass.

Figs. 8 and 9 summarize the effect of strain rate and type of TMCP strategy on the peak and flow stresses. It has been observed that the flow and peak stresses increase as the applied strain rate increases (Fig. 8). In SP TMCP strategy, flow
and peak stresses increase from 90 to 140 MPa and from 155 to 327 MPa, respectively, as the strain rate increases from 0.01 to 1.0 s\(^{-1}\). The same behavior is observed for DP TMCP strategy. Yang and Li [9] studied the flow manner of a low-carbon steel during hot deformation and found that applying large strain deformation at low deformation temperature slightly higher than austenite to ferrite transformation temperature at high strain rate followed by rapid cooling lead to formation of homogeneous distribution of UFF grains; hence promote the flow stress. Their results of the effect of strain rate on flow stress are in agreement with the current results.

Type of TMCP strategy, i.e. SP, DP or MP, affects the peak and flow stresses (Fig. 9). At constant strain rate of 0.1 s\(^{-1}\), peak stress increases from 226 MPa after SP TMCP strategy to 354 MPa after DP and 296 MPa after MP TMCP strategies, respectively. It has been observed that DP TMCP strategy reveals the highest value of the peak stress at all strain rates with an intermediate value of the flow stress.

3.2.2. TMCP strategy vs. strain hardening index

Fig. 10 shows the alteration of the strain hardening index with a strain rate of TMCP strategy. The value of strain hardening index increases with increasing strain rate. Strain hardening index raises from 0.175 to 0.357, as the strain rate rises from 0.01 to 1 s\(^{-1}\), for SP TMCP strategy.

The variation of the strain hardening index with number of passes and type of TMCP strategy at a constant strain rate of 0.1 s\(^{-1}\) is shown in Fig. 11. Increasing number of passes during DP and MP TMCP strategies enhances the value of strain hardening index. The final pass of MP TMCP strategy exhibits the highest value of strain hardening index, followed by DP whilst SP shows the lowest strain hardening index.

3.2.3. TMCP strategy vs. Zener–Hollomon parameter

Zener–Hollomon (Z-H) parameter is considered a representative of deformation conditions [1,19,20]. Z-H parameter is
utilized to describe the influence of deformation temperature and strain rate on microstructural refinement and flow behavior during TMCP [7]. Z-H parameter is a function of flow stress and directly proportional with it. Cao et al. [20] presented a systematic review on severe plastic deformation (SPD)-induced grain refinement and other microstructural evolutions of different metallic materials. They stated that increasing Z-H parameter enhances the grain refinement. Therefore, Z-H parameter can be used to optimize the processing parameters during TMCP [7]. Cao et al. [20] employed the constitutive equation, \( Z = \dot{\varepsilon} \exp(Q/RT) = f(\sigma) \), to describe TMCP process, where \( Z \) is the Zener–Hollomon parameter, \( Q \) is the activation energy of TMCP, \( R \) is the gas constant, \( T \) is the TMCP absolute temperature and \( \sigma \) is the flow stress [1,7–9,19,20]. The activation energy \( Q \) is a function only in the amount of deformation. Yang and Li [9] also calculated \( Q \) as a function of strain using an equation of Arrhenius-type model, this equation was utilized to estimate \( Q \) for the undertaken TMCP strategies, as presented in Table 2. It has been observed that \( Q \) increases with number of passes in DP and MP TMCP strategies, this may be attributed to the strain hardening occur in the previous pass so higher flow stress and activation energy is required.

Fig. 12 illustrates the variation of the Z-H parameter with a strain rate of TMCP strategy. By simultaneous observation of Figs. 8 and 12, it is found that as the strain rate increases Z-H parameter and flow stress increase for each pass. Increasing the flow stress does not consider an advantage, where it means the need for high rolling mill capacity. Fig. 13 shows the variation of Z-H parameter with TMCP strategy at strain rate of 0.1 s⁻¹. Z-H parameter is affected by TMCP strategy and raises with raising number of passes.

3.2.4. TMCP strategy vs. total TMCP strategy time
The time of implementation of the TMCP strategy on the production line is one of the most important factors that
must be taken into account. The longer the strategy takes to implement, the more expensive it becomes. In the current work, total TMCP strategy time is considered. Table 2 presents the timing schedule of the undertaken SP, DP and MP TMCP strategies at a constant strain rate of 0.1 s⁻¹. SP TMCP strategy takes 71.1 s to accomplish, DP TMCP strategy takes 69.1 s, whilst MP TMCP strategy takes 106 s. Therefore, from cost saving point of view, DP TMCP strategy is the most efficient to achieve time shortening requirement and hence improves the productivity.

### Table 2 – Activation energy and timing schedule of the different TMCP strategies at 0.1 s⁻¹ strain rate.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Passes</th>
<th>T (°C)</th>
<th>Deformation/pass (%)</th>
<th>t (s)</th>
<th>Q (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP-TMCP</td>
<td>One pass</td>
<td>0-1000</td>
<td>0</td>
<td>31.7</td>
<td>152.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>45</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000-23</td>
<td>0</td>
<td>24.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>45</td>
<td>71.1</td>
<td></td>
</tr>
<tr>
<td>DP-TMCP</td>
<td>First pass</td>
<td>0-1000</td>
<td>0</td>
<td>31.7</td>
<td>151.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>0</td>
<td>10</td>
<td></td>
</tr>
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<td></td>
<td></td>
<td>1000</td>
<td>28</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second pass</td>
<td>1000-900</td>
<td>0</td>
<td>0.5</td>
<td>152.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900</td>
<td>25</td>
<td>2.8</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>900-23</td>
<td>0</td>
<td>21.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>53</td>
<td>69.1</td>
<td>–</td>
</tr>
<tr>
<td>MP-TMCP</td>
<td>First pass</td>
<td>0-1000</td>
<td>0</td>
<td>31.7</td>
<td>152.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>0</td>
<td>10</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>16</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second pass</td>
<td>1000-950</td>
<td>0</td>
<td>10</td>
<td>153</td>
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<tr>
<td></td>
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<td>16</td>
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<td>Third pass</td>
<td>950-900</td>
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<tr>
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<td></td>
<td>900</td>
<td>14</td>
<td>1.4</td>
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<tr>
<td></td>
<td>Fourth pass</td>
<td>900-850</td>
<td>0</td>
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<td>167</td>
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<tr>
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<td></td>
<td>850</td>
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<tr>
<td></td>
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<td>Total</td>
<td>57</td>
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</table>

![Z-H Parameter Vs. TMCP Strategy](image)

**Fig. 12** – Variation of Z-H parameter with strain rate of TMCP strategy.

### 3.3. Optimizing TMCP strategy type

In order to determine the optimum type of TMCP strategy, i.e. SP, DP and MP TMCP strategies, the strategies have to be compared at constant strain rate. Fig. 14 compares different aspects of the influence of each TMCP strategy at a strain rate of 0.1 s⁻¹, these aspects include peak stress, flow stress, average grain size, total time of strategy implementation and Z-H parameter (average value with error bars indicating the range within each strategy). It has been observed that the finest
microstructure, of 6.4 μm average grain size, with the highest peak stress of 354 MPa with intermediate values flow stress and Z-H parameter can be achieved in the shortest time of 69.1 s using the DP TMCP strategy. Therefore, DP TMCP strategy combines the improvement in the flow characteristics (finest microstructure and highest peak stress) and productivity characteristics (lowest flow stress and processing time).

4. Conclusions

The demand of applying light deformation/pass in multi-pass TMCPs instead of heavy deformation single pass TMCPs is an inevitable need of the practical industrial approaches to be suitable to potential industrial rolling mills, i.e. maximum capacity required. Therefore, the current work has been proposed different TMCP strategies. These TMCP strategies involve applying different plane-strain hot compression regimes with 45–57% total accumulative strain, taking the effect of strain rate in consideration. The effects of these TMCP strategies, at different strain rates (0.01–0.1–1.0 s\(^{-1}\)), on the microstructure and flow-productivity characteristics of low carbon steel had been studied. Industrial requirements such as reducing processing cost and promoting strength are taken into consideration during designing the TMCP strategies. The major conclusions derived from the present study are summarized below:

1. Microstructures after all TMCP strategies reveal ferrite refinement and the flow curves show continuous strain hardening. This asserts that the working grain refinement mechanism during all TMCP is DSIT without any dynamic recovery and recrystallization refining/softening mechanisms.
2. DP TMCP strategy maximizes the DSIT effect on ferrite grain refinement than SP and MP TMCP strategies, at constant strain rate, and results in the finest average grain size of 6.4 μm. This is attributed to that DP TMCP strategy applies sufficient amount of deformation/pas at a temperature higher than the critical transformation temperature of austenite to ferrite. These processing conditions are suitable for the beginning and progressing of the DSIT on the opposite of SP and MP TMCP strategies.

3. Increasing strain rate from 0.01 to 1.0 s⁻¹ increases the flow and peak stresses and strain hardening indexes, regardless the type of the applied TMCP strategy.

4. In DP and MP TMCP strategies, the values of the flow and peak stresses, strain hardening indexes and the activation energies of each pass in TMCP strategies increase as the number of passes increase at constant strain rate.

5. Z-H parameter increases with increasing flow stress as the strain rate and number of passes in DP and MP TMCP strategies increase.

6. DP TMCP strategy is the optimum TMCP strategy that addresses the performance, cost and productivity requirements. It results in the finest average grain size, highest peak stress, an intermediate value of Z-H parameter and hence suitable value of the flow stress, in addition, it requires the shortest processing time as compared to SP and MP TMCP strategy.

Conflicts of interest

The authors declare no conflicts of interest.

REFERENCES


