FEM simulation of dynamic recrystallization during asymmetric hot rolling of high-speed steel M2

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Abstract. Dynamic recrystallization of high-speed steel (HSS) M2 occurs through a discontinuous mechanism, involving nucleation and growth of strain-free grains. The initiation and completion of discontinuous dynamic recrystallization (dDRX) must be carried out in a single rolling pass. The time for 99% dDRX depends on the critical strain, strain rate and equivalent strain, that generated in the workpiece material in a single rolling pass. The level of equivalent strain plays a key role in terms of the possibility to complete dDRX. High equivalent strain in conventional hot rolling for a single pass is limited by too high rolling forces. High equivalent strain at low rolling forces can be achieved by asymmetric hot rolling. Asymmetric rolling is a process based on purposefully created differences in the circumferential speeds of the work rolls. For such a process, a degree of asymmetry is defined by a speed ratio of the work rolls. The speed ratio is one of the most important parameters of the process, affecting the level of equivalent strain and the rolling force. In this work the single-pass asymmetric hot rolling process of HSS M2 at different temperatures in the range 850-1150 °C was simulated by FEM and JMAK model. The effects of speed ratio and thickness reduction on equivalent strain and rolling force were investigated. The effects of equivalent strain, strain rate and temperature on the recrystallized volume fraction and the average size of a dynamically recrystallized grains of HSS M2 are presented. Symmetric and asymmetric hot rolling processes are compared.

Introduction

The metal forming industry can use different methods for grain refinement in metals and alloys. One of these methods is based on grain refinement directly in the process of hot working due to the dynamic recrystallization (DRX). The DRX phenomena can occurring in different thermo-mechanical processing conditions for various metals and alloys. Several types of DRX are exist: discontinuous dynamic recrystallization (dDRX), continuous dynamic recrystallization (cDRX) and geometric dynamic recrystallization (gDRX). Different types of DRX are associated with different types of mechanisms of the formation of a new grain structure. Detailed characterization of these three types of DRX processes is given in the literature [1-3].

The dDRX is the most extensively studied recrystallization process. The dDRX occurs through a discontinuous mechanism, involving nucleation and growth of strain-free grains. dDRX operates in low to medium stacking fault energy materials at high temperatures ($T > T_m$) [1-3]. It is generally accepted that dDRX mainly initiates by strain induced bulging of original grain boundaries and a necklace structure which is composed of fine equiaxed recrystallized grains is formed. With regard to grain refinement, the important point is that dynamic recrystallization not only produces more refinement than the metadynamic recrystallization but also leads to considerably finer microstructures than conventional static recrystallization [1]. The dDRX has attracted more and more interests since it is the closest method to industrial practices.

The dDRX process initiates at the critical strain ε_c. The volume fraction X of dynamic recrystallization, can be calculated by JMAK model: $X = 1 - \exp(-\beta t^k)$, where β and k are coefficients and t is the time for dDRX to occur [4]. The time for 99% dDRX (when $X = 0.99$) strongly depends on strain ε and strain rate $\dot{\varepsilon}$. Large strain (e.g. $\varepsilon \geq 1$) are required for uniform grain refinement. The application of insufficient strain can lead to the presence of mixed grain sizes. Thus, strain is a key parameter that determines not only the initiating of dDRX, but also the possibility of its full completion. Significant grain refinement can be achieved at 99% dDRX due to large strain single-pass hot working at the lower temperature range.

The dDRX in hot working has been repeatedly studied for austenitic [5], microalloyed [6]. low-carbon [7] and high-speed tool steels (HSSs) [4,8]. HSSs represent an important class of materials for the manufacture of cutting tools. HSSs are used for most of the common types of cutting tools including lathe tools, drills, reamers, taps, milling cutters, end mills, hobs, saws, broaches, etc. The improvement of HSSs is carried out in the direction of finding the ways to improve microstructure and mechanical properties during hot working. Hot rolling is the main process for obtaining long semi-finished products (round bars, plates, sheets, strips, etc.) from HSSs. The conventional technologies include radial-shear hot rolling and plate/strip hot rolling. HSSs are difficult to deform, so conventional hot rolling is carried out with a large number of passes in order not to exceed the maximum allowable rolling forces. HSSs are usually hot rolled at high temperatures, e.g., 1100 °C to 1150 °C for the M2 grade, with the final rolling pass carried out at temperatures not less than 850 °C. In this range, their flow stress may reach 350…450 MPa, the same as the ultimate strength of ordinary steels at room temperature. Therefore, the ability to provide 99% dDRX in HSSs during single-pass hot rolling, especially at the lower temperature range is limited by too high rolling forces. Rolling force can be reduced due to the asymmetry of the hot rolling process by purposefully created difference in the circumferential speeds of the work rolls [9,10]. For such a process, a degree of asymmetry is defined by a speed ratio (SR) of the work rolls. The SR is one of the most important parameters of the process. Rolling with different circumferential speeds of the work rolls when both rolls are independently driven by two motors, is the most suitable way to implement asymmetric hot rolling in industry. However, studies of the effect of asymmetric hot rolling on the kinetics of dDRX of HSSs are yet unknown.

In this work the large strain single-pass asymmetric hot rolling process of HSS M2 at different temperatures in the range 850-1150 °C was simulated by FEM and JMAK model. The effects of speed ratio and thickness reduction on equivalent strain and rolling force were investigated. The effects of strain, strain rate and temperature on the recrystallized volume fraction and the average size of a dynamically recrystallized grains of HSS M2 are presented. Symmetric and asymmetric hot rolling processes are compared. The results of investigation can be used for design of effective technology of manufacturing HSS M2 with improved microstructure and mechanical properties.

Research Method

A coupled deformation and heat transfer simulation of the hot rolling was carried out using the commercial FEM code QForm 2D. Symmetric and asymmetric hot rolling processes were simulated and compared. Asymmetry was purposefully created by difference in the circumferential speeds of the work rolls, while the roll diameters were the same. The diameters of the work rolls were D = 340 mm, and the rolls were assumed as rigid. The angular speed of the upper (fast) work roll was 10 rpm in all simulation variants. Asymmetry was created by decreasing the angular speed of the lower (slow) work roll from 1.1 to 3.0 times with a step of 0.1. The initial thickness of the strip was 3.15 mm in all simulation variants. Single-pass rolling to the final thickness of 1.0 mm was performed. Thickness reduction corresponded to 68.25%. The modeling of the processes was performed at different initial temperatures: 1150, 1100, 1000, 900 °C with taking into account the increment of the metal's temperature due to the thermal effects of deformation and friction. Hot rolling was carried out without front and back tensions. High-speed tool steel AISI M2 was chosen as a material for the strip. AISI D2 from QForm 2D material library was chosen as a material for work rolls. The thermal constants of materials used in FEM simulations are shown in Table 1. Levanov's friction model (1) was used between rolls and strip. During hot rolling of steels friction factor m varies in the range of 0.7-1.0. In the present research the friction factor was assumed as constant in all simulation variants: $m = 0.85$.

$$\tau = mk\left(1 - e^{-1.25\frac{\sigma_n}{\sigma}}\right). \tag{1}$$

where τ is the frictional stress; m is the friction factor; k is the shear yield stress; σ_n is the normal contact pressure; σ is the flow stress.

Table 1. Properties of materials used in FEM simulation.

Material	Thermal conductivity, W/(m×K)	Heat capacity, J/(kg×K)	Heat transfer coefficient between work rolls and strip, W/(m^2×K)	Heat transfer coefficient between work rolls/strip and air, W/(m^2×K)	Environment temperature, °C
AISI M2	28.0	674	10000	30	20
AISI D2	21.5	460	10000	30	20

In order to accurately describe the flow behavior of HSS M2 in hot deformation, dDRX should be considered. Schematic representation of the stress-strain curve during dDRX is shown in Fig. 1. First, there is work hardening from σ_0 up to peak stress σ_p at peak strain ε_p then working softening up to steady stress σ_{ss} at steady strain ε_{ss} if no failure occurs.

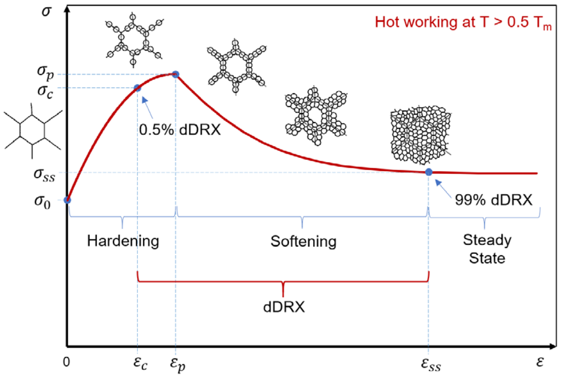

Fig. 1. Diagram of the stress-strain curve during dDRX.

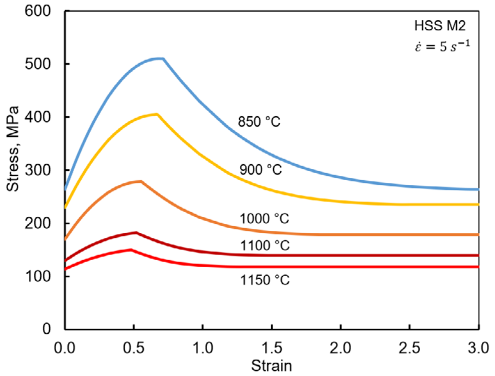

Fig. 2. Stress-strain curves of HSS M2 used in FEM.

Based on experimental values of σ_0, σ_c, σ_p, σ_{ss} and ε_c, ε_p, ε_{ss} from [4,8,11-13] the stress-strain curves for HSS M2 were approximated and used in FEM simulations. Equations (2)-(7) were also used (see below). Obtained stress-strain curves corresponded to the following ranges: ε = 0…3, $\dot{\varepsilon}$ = 0.1…50 s^{-1}, T = 850…1150 °C. As an example, stress-strain curves for different temperatures are shown in Fig. 2. A critical strain ε_c is necessary in order to initiate dynamic recrystallization. This occurs somewhat before the peak stress σ_p and peak strain ε_p of the stress-strain curve. Based on the experimental data from [11-13], the peak strain ε_p as a function of the Zener-Hollomon parameter Z was approximated:

$$\varepsilon_p = 0.0554 \cdot Z^{0.0515}. \tag{2}$$

$$Z = \dot{\varepsilon} exp\left(\frac{Q_{HW}}{RT}\right). \tag{3}$$

where $Q_{HW} = 455$ kJ/mol is the hot working activation energy [4], $R = 8.314$ J/mol/K is the universal gas constant, T is absolute temperature.

The relationship between critical strain ε_c and peak strain ε_p for HSS M2 was assumed as follows [4]: $\varepsilon_c = 0{,}65 \cdot \varepsilon_p$. The relationship between critical stress σ_c and peak stress σ_p was assumed as follows: $\sigma_c = 0{,}95 \cdot \sigma_p$.

The volume fraction X of dynamic recrystallized grain:

$$X = 1 - \exp\left(-\beta\left(\frac{\varepsilon - \varepsilon_c}{\dot{\varepsilon}}\right)^k\right). \tag{4}$$

Experimental coefficients β and k, depending on temperature T and strain rate $\dot{\varepsilon}$, for HSS M2 were taken and calculated from [4].

Taking into account the changing of volume fraction X of dynamic recrystallized grain the softening from the peak stress σ_p to the steady stress σ_{ss} was expressed:

$$\sigma_{p\_ss} = \sigma_p - \left(\sigma_p - \sigma_{ss}\right)\frac{(X - X_p)}{(X_{ss} - X_p)}. \tag{5}$$

where X_p and $X_{ss} = 0.99$ are volume fractions of dynamic recrystallized grain at peak strain ε_p and ε_{ss} respectively.

The time t_{ss} for 99% dDRX, depends on the steady state stress σ_{ss} in the following relationship [4]:

$$t_{ss} = A(\sinh \alpha\sigma_{ss})^n \exp\left(\frac{Q_{DRX}}{RT}\right). \tag{6}$$

where A is a material constant (Table 2), $n = -4.6$ is the stress exponent, $Q_{DRX} = 361$ kJ/mol is the steady state stress activation energy, $R = 8.314$ J/mol/K is the universal gas constant, T is absolute temperature, and $\alpha = 0.012$ MPa [4].

Table 2. Material constant A depending on temperature.

Temperature, °C	1150	1100	1000	900	850
$\log A$	-12.65	-12.49	-12.47	-12.22	-12.15

The time t_{ss} for 99% dDRX can also be calculated by the following:

$$t_{ss} = \frac{\varepsilon_{ss} - \varepsilon_c}{\dot{\varepsilon}}. \tag{7}$$

The steady state stress σ_{ss} was expressed from (6) with taking into account (7):

$$\sigma_{ss} = \frac{1}{\alpha} \sinh^{-1} \left[\left(\frac{1}{A} \left(\frac{\varepsilon_{ss} - \varepsilon_c}{\dot{\varepsilon}} \right) \exp\left(-\frac{Q_{DRX}}{RT} \right) \right)^{\frac{1}{n}} \right]. \tag{8}$$

The steady state strain ε_{ss} was expressed from (4) at $X = X_{ss} = 0.99$:

$$\varepsilon_{ss} = \varepsilon_c + \dot{\varepsilon} \left[-\frac{1}{\beta} \ln(1 - X_{ss}) \right]^{\frac{1}{k}}. \tag{9}$$

The initial grain size D_0 was taken equal to 90 μm. The dynamic recrystallization grain size D_{dDRX} depends on the Zener-Hollomon parameter Z according to the following equation [4]:

$$D_{dDRX} = 2930 \cdot Z^{-0.15}. \tag{10}$$

Only dDRX was simulated. Static/metadynamic recrystallization and grain growth at high temperature were not simulated. The average grain size D_{avg} was calculated according to the "mixture" rule:

$$D_{avg} = X \cdot D_{dDRX} + (1 - X) \cdot D_0. \tag{11}$$

Simulation Results and Discussion

The dynamic recrystallization grain size D_{dDRX} decreases with decreasing temperature and increasing strain rate. Grain size up to ≈2 μm, ≈1.5 μm and ≈1.0 μm can be obtained, respectively, at temperatures of 1000 °C, 900 °C, 850 °C and a strain rate of 50 s^{-1} (Fig. 3). However, this grain refinement can be achieved in case when 99% dDRX has occurred due to a single-pass large strain ε, which is equal to or greater than the steady state strain ε_{ss}. Interrelation between steady state strain, strain rate and temperature for HSS M2 is shown in Fig. 4. For example, strain value ε must be at least 2.06 in order to provide 99% dDRX at 1000 °C and 20 s^{-1}. If strain rate increases up to 50 s^{-1}, then strain value ε must be at least 2.25 at the same temperature. At lower temperatures, strain should be even higher. At 900 °C strain value ε must be at least 2.82 in order to provide 99% dDRX at 50 s^{-1} (Fig. 4). The conventional hot rolling process cannot provide such large strain values in one pass, especially over the entire section of the strip.

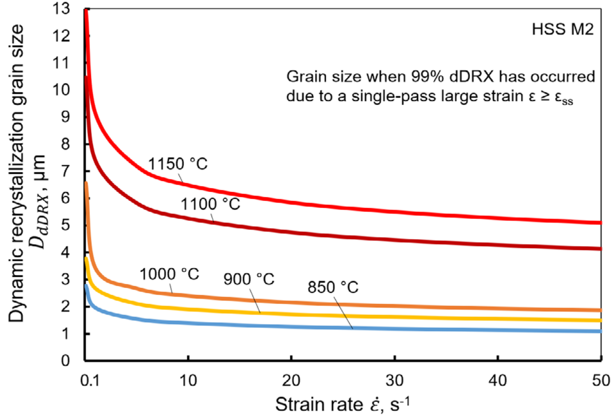

Fig. 3. Influence of strain rate and temperature on dynamic recrystallization grain size

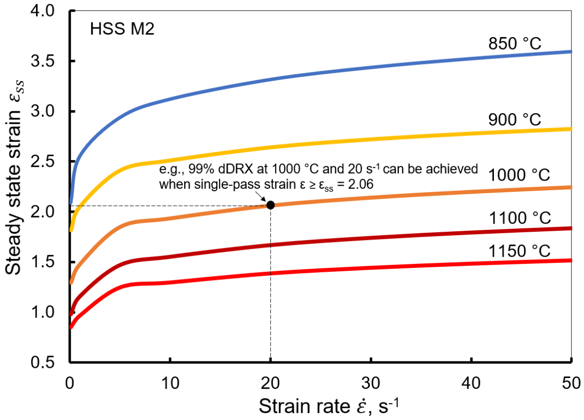

Fig. 4. Interrelation between steady state strain, strain rate and temperature for HSS M2.

Large strain can be achieved by single-pass asymmetric rolling. Work rolls speed ratio was varied from 1.0 (symmetric rolling) up to 1.1…3.0 with step 0.1 (asymmetric rolling). The initial temperature of the strip was also varied at the following values: 1150, 1100, 1000, 900 °C. A comparative analysis of many simulation variants showed that the finest average grain size in combination with a fairly uniform grain distribution over the strip thickness was achieved by asymmetric rolling with a work roll speed ratio of 1.5 at T = 1000 °C. Speed ratio of 1.5 means that the speed of upper work is 1.5 times faster than lower work roll. The average grain size of 2.9 µm in the center layer of the strip was achieved by asymmetric rolling (Fig. 5) in comparison with grain size of 14.2 µm obtained by symmetric rolling (Fig. 6). A decrease in the grain size in the central layer of the strip was achieved by almost 5 times.

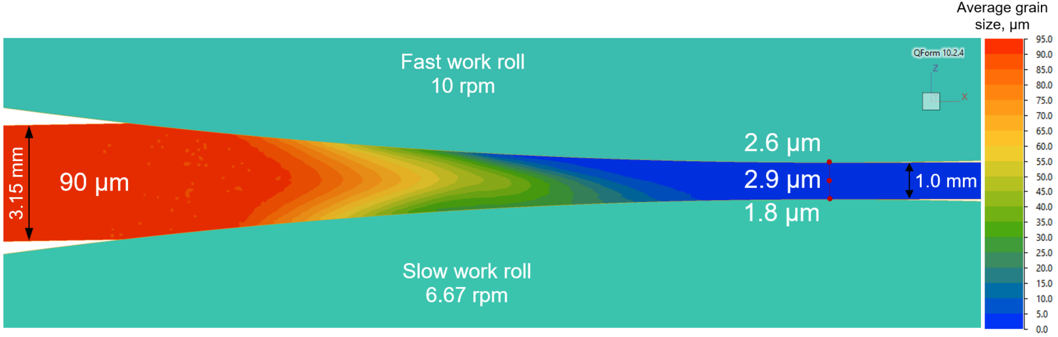

Fig. 5. Evolution of the average grain size during asymmetric rolling (SR = 1.5).

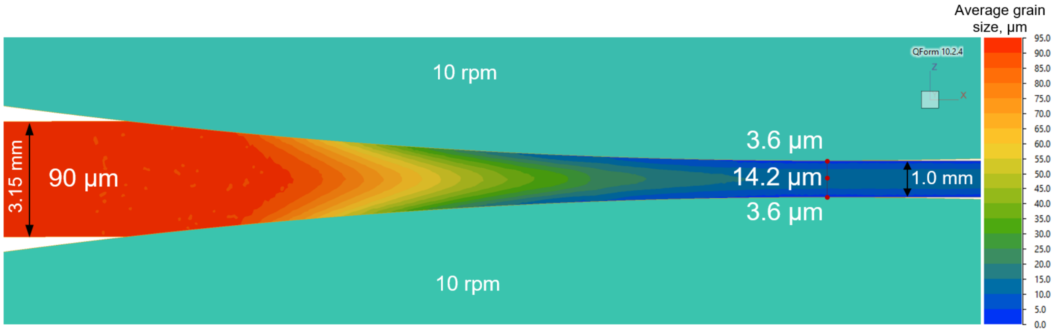

Fig. 6. Evolution of the average grain size during symmetric rolling.

At the same time, due to asymmetric rolling, a fairly uniform distribution of fine grain over the strip thickness was also achieved (Fig. 7). This is due to a more uniform distribution of strain over the thickness (Fig. 8).

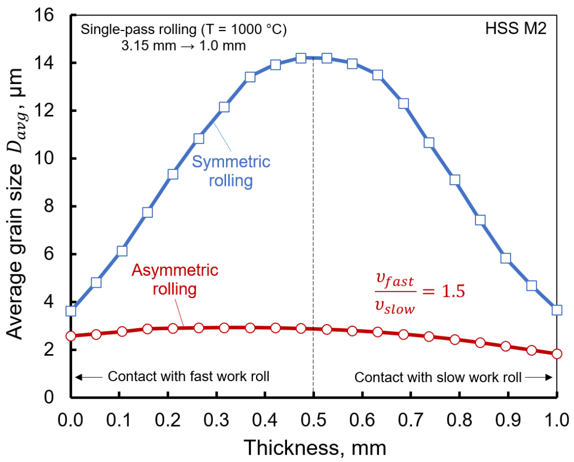

Fig. 7. Distribution of the average grain size over the strip thickness.

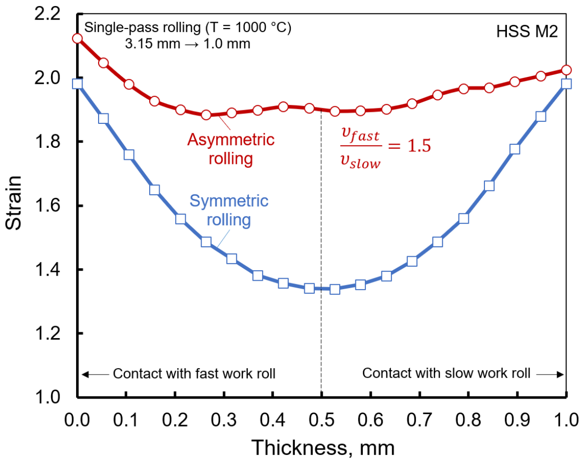

Fig. 8. Strain distribution over the strip thickness.

Temperature field during asymmetric rolling is shown in Fig. 9. The temperature in the deformation zone decreases from the initial 1000 °C to 860 °C at the contact with the slow work roll. The temperature difference at the contact with the upper and lower roll leads to an additional asymmetry factor. The lower contact temperature with the slow roll is due to the longer contact time. With symmetrical rolling, the temperature at the contact with the work rolls is also significantly reduced from 1000 °C to 890 °C (Fig. 10). Lower temperature and higher strain in the surface layers lead to grain refinement in both symmetric and asymmetric rolling. However, only asymmetric rolling makes it possible to refine the grain over the entire thickness of the strip due to the occurring of 100% dynamic recrystallization (Fig. 11). At the same time, the force during asymmetric rolling is significantly lower in comparison with symmetric rolling (Fig. 12).

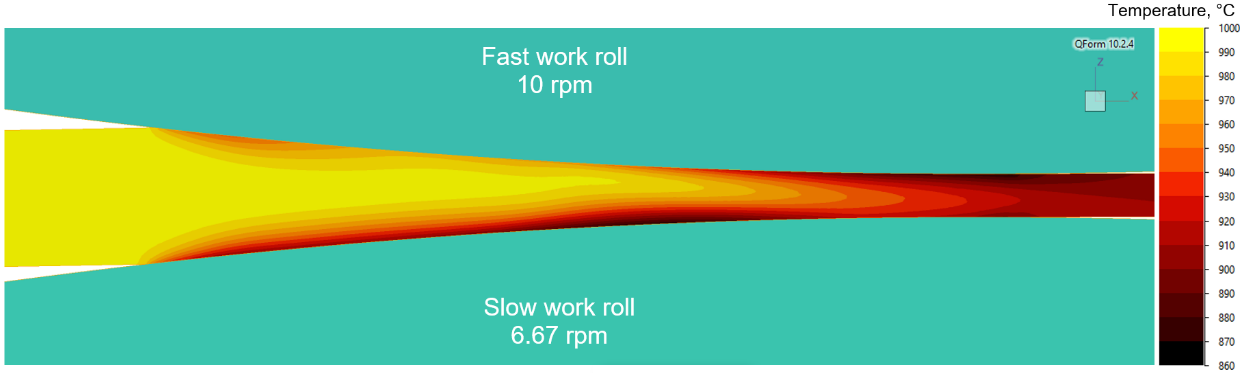

Fig. 9. Temperature field during asymmetric rolling.

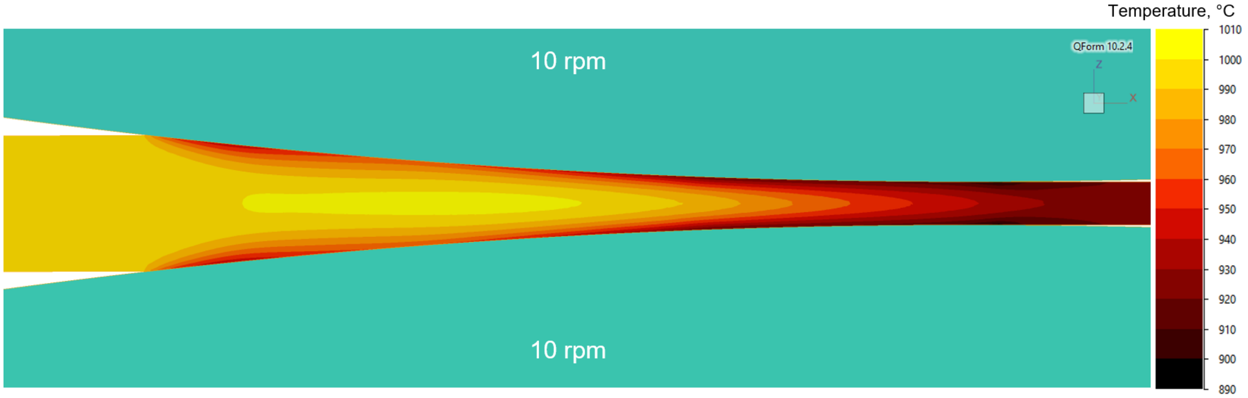

Fig. 10. Temperature field during symmetric rolling.

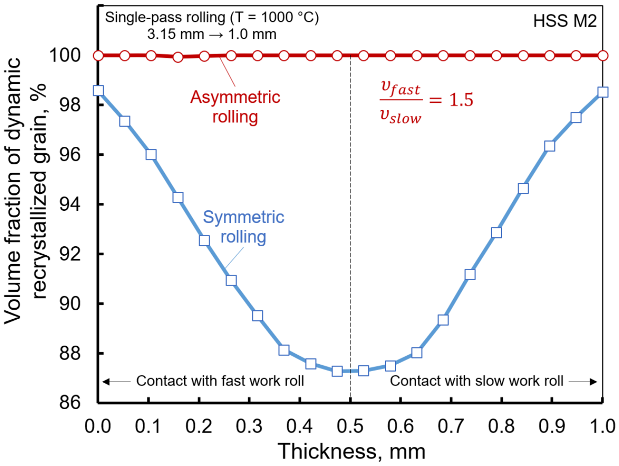

Fig. 11. Distribution of the volume fraction of dynamic recrystallized grain over the strip thickness.

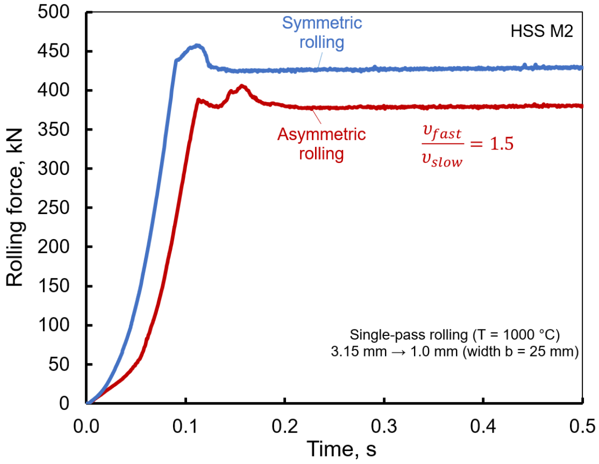

Fig. 12. Comparison of rolling forces during symmetric and asymmetric rolling.

Conclusion

Asymmetric hot rolling is a process which can provide the occurring of 99% dDRX in the difficult-to-deform high-speed steel M2 due to single-pass large strain at the lower temperature range. Large strain can be achieved by less rolling force in comparison with symmetric rolling.

In the present study the finest average grain size in combination with a fairly uniform grain distribution over the strip thickness was achieved by asymmetric rolling with a work roll speed ratio of 1.5 at T = 1000 °C. The average grain size of 2.9 μm in the center layer of the strip was achieved by asymmetric rolling in comparison with grain size of 14.2 μm obtained by symmetric rolling. A decrease in the grain size in the central layer of the strip was achieved by almost 5 times. However, experimental studies are required to confirm the results of FEM simulations.

The results of investigation can be used for design of effective technology of manufacturing HSS M2 with improved microstructure and mechanical properties. The main difficulty in the development of asymmetric hot rolling technology is to determine the optimal speed ratio of the work rolls.

Acknowledgements

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References

[1] J.J. Jonas, Dynamic recrystallization - scientific curiosity or industrial tool? Mater. Sci. Eng. A 184 (1994) 155-165. https://doi.org/10.1016/0921-5093(94)91028-6

[2] K. Huang, R.E. Logé, A review of dynamic recrystallization phenomena in metallic materials, Materials & Design 111 (2016) 548-574. https://doi.org/10.1016/j.matdes.2016.09.012

[3] H.J. McQueen, Development of dynamic recrystallization theory, Mater. Sci. Eng. A 387-389 (2004) 203-208. https://doi.org/10.1016/j.msea.2004.01.064

[4] C.A.C. Imbert, H.J. McQueen, Dynamic recrystallization of A2 and M2 tool steels, Mater. Sci. Eng. A 313 (2001) 104-116. https://doi.org/10.1016/S0921-5093(01)00974-1

[5] A. Dehghan-Manshadi, M.R. Barnett, P.D. Hodgson, Hot deformation and recrystallization of austenitic stainless steel: part I. dynamic recrystallization, Metall. Mater. Trans. A. 39 (2008) 1359-1370. https://doi.org/10.1007/s11661-008-9512-7

[6] S.H. Cho, K.B. Kang, J.J. Jonas, Dynamic, static and metadynamic recrystallization of a Nb-microalloyed steel, ISIJ Int. 41 (2001) 63-69. https://doi.org/10.2355/isijinternational.41.63

[7] S.S. Dhinwal, C. Ernould, B. Beausir, Facilitating the occurrence of dynamic recrystallization in plain extra low-carbon steel by warm asymmetric rolling, Materials Characterization 189 (2022) 111942. https://doi.org/10.1016/j.matchar.2022.111942

[8] R. Milovic, D. Manojlovic, M. Andjelic, D. Drobnjak, Hot workability of M2 type high-speed steel, Steel research 63 (1992) 78-84. https://doi.org/10.1002/srin.199200474

[9] D. Pustovoytov, A. Pesin, P. Tandon, Asymmetric (hot, warm, cold, cryo) rolling of light alloys: a review, Metals 11 (2021) 956. https://doi.org/10.3390/met11060956

[10] G. Vincze, F.J.P. Simões, M.C. Butuc, Asymmetrical rolling of aluminum alloys and steels: a review, Metals (2020) 10, 1126. https://doi.org/10.3390/met10091126

[11] C. Imbert, N.D. Ryan, H.J. McQueen Hot workability of three grades of tool steel, Metallurgical Transactions A 15 (1984) 1855-1864. https://doi.org/10.1007/BF02664899

[12] C. Imbert, H.J. McQueen, Hot Ductility of Tool Steels, Canadian Metallurgical Quarterly 40 (2001). 235-244. https://doi.org/10.1179/000844301794388461

[13] C. Imbert, H.J. McQueen, Peak strength, strain hardening and dynamic restoration of A2 and M2 tool steels in hot deformation, Mater. Sci. Eng. A 313 (2001) 88-103. https://doi.org/10.1016/S0921-5093(01)00976-5