Effects of cooling methods and cooling conditions on behavior of thermal distortion and stress generation of steel blooms cast continuosly on reverse transformation treatment

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In recent years, the treatment of reverse transformation has been adopted in the HCR process of CC-Blooming for steel production to prevent surface cracking on blooming. However, the quenching of bloom in this treatment occasionally causes some troubles, such as occurrence of thermal distortion of bloom and quenching cracks. On the behaviour of thermal distortion of bloom and the generation of stress in cross section of bloom, the effects of kinds of cooling methods (immersion, spray, mist-spray cooling) and cooling conditions for reverse transformation treatment, were analysed in order to prevent these troubles by a model of metallo-thermo-mechanics in this study. The following results were obtained from these analyses. In the several cooling methods and cooling conditions, the time required for the reverse trans- formation treatment under various cooling conditions were clarified. The effects of the three types of cooling methods and various cooling conditions on the cross-sectional shape of the cast bloom after cooling and the stress generated during cooling were analysed from the viewpoint of the several kinds of transformation behaviour and thermal shrinkage. The optimum cooling methods and necessary cooling conditions for shortening the required cooling time and preventing the occurrence of quenching cracks were revealed from the analyses.

KEYWORDS: REVERSE TRANSFORMATION TERATMENT, CONTINUOUS CASTING, HCR PROCESS, METALLO, THERMO MECHANICS, THERMAL DISTORTION, STRESS GENERATION;

INTRODUCTION

In recent years, the treatment of reverse transformation has been adopted in the HCR process of CC-Blooming for steel production to prevent surface cracking on blooming. This treatment is very effective for toughening of the bloom surface of steel and prevention of occurrence of cracks on hot rolling by refinement of austenite grains (1)-(4). However, the quenching of bloom in this treatment occasionally causes some troubles, such as occurrence of thermal distortion of bloom and quenching cracks. The causes and mechanisms of the occurrence of thermal distortion and quenching cracks haven't been revealed sufficiently. The behavior of thermal distortion of bloom and the generation of stress in cross section of bloom causing quenching cracks by third cooling for treatment of reverse transformation are affected by kinds of third cooling methods (immersion, spray, mist-spray cooling) and cooling conditions for reverse transformation treatment.

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In this study, the causes and mechanisms of thermal distortion and quenching crack and the effects of kinds of cooling methods and cooling conditions of reverse transformation treatment were analyzed in order to prevent these troubles by the model of metallo-thermo-mechanics (5), (6). The cooling methods considered in these analyses were immersion cooling, spray cooling and mist-spray cooling.

ANALYSIS METHOD

ANALYSIS MODEL

Since the distribution of temperature and stress/strain and their transition and behavior of phase transformation affect mutually during third cooling, analyses combined distortion analysis with heat transfer analysis and analysis of phase transformation behavior are necessary to examine thermal distortion and stress generation considering these mutual effects. Therefore, the behavior of thermal distortion and stress generation were analyzed by the model of metallo-thermo-mechanics shown in Fig.1(5), (6): COSMAP (7) in this study. Thermo-elastic-plastic analysis, analysis of heat transfer and analysis about transformation behavior are combined in this model considering of thermal shrinkage and expansion, shrinkage and expansion accompanying transformation. The effects of cooling methods and cooling conditions on the behavior of thermal distortion and stress generation were studied by this model.

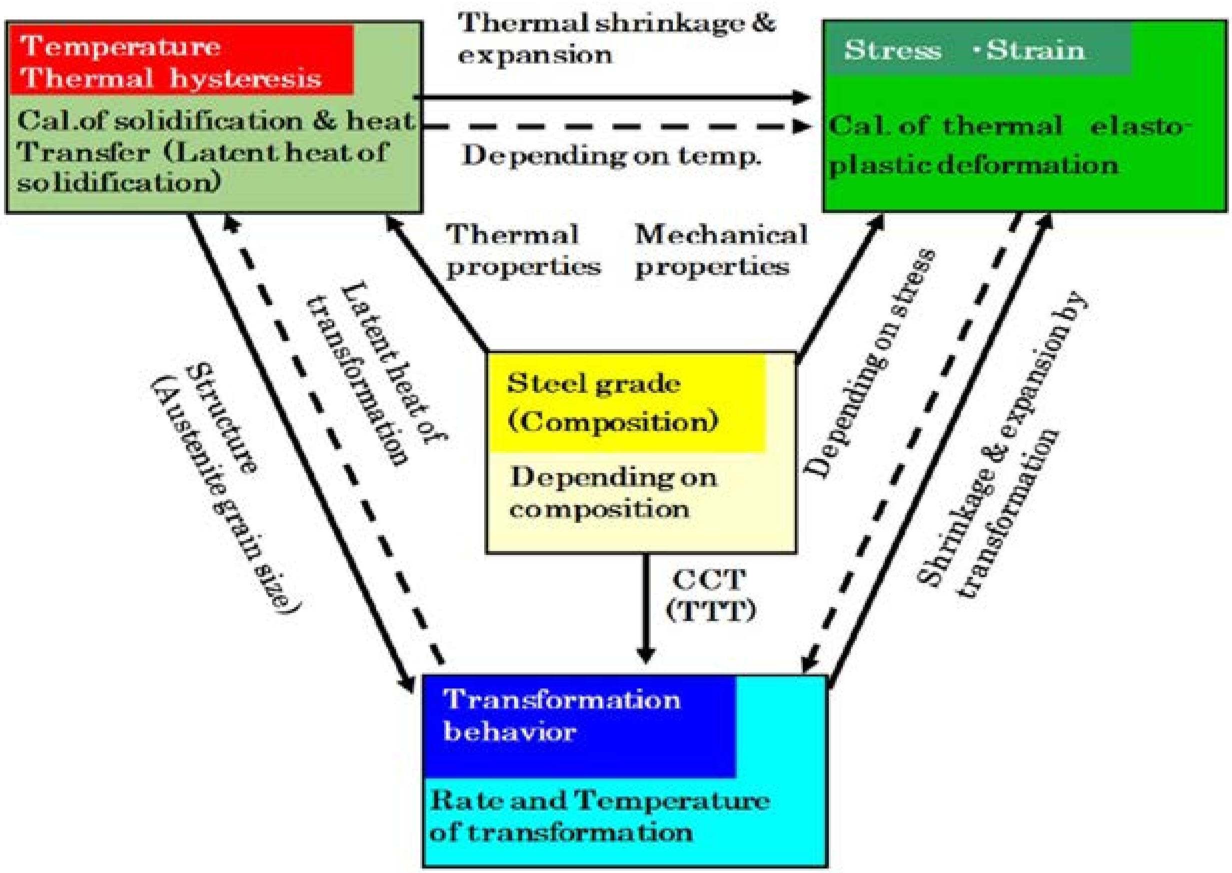


Fig.1 – Schematic view of the model of metallo-thermo-mechanics. (5)

ANALYSIS CONDITIONS

The analyses were performed using a finite element method two-dimensional model for total cross section of a bloom having a square cross section of 200 mm (thickness) x 200 mm (width). The analyzed steel type was case hardening steel SCr420(JIS), and the transformation behavior of this steel type was estimated in consideration of the CCT diagram measured in a coarse austenite structure similar to that of bloom as cast continuously (8).

In these calculations, the solidification calculation was not performed, but the calculations were carried out under the following conditions. The entire bloom was once heated to 1123K, and then was cooled under various cooling methods and cooling conditions, until the austenitic phase in the surface layer of the bloom in the range of 10 mm was transformed into a low-temperature phase for the refinement of austenite structure by reverse transformation. Therefore, the calculation was performed under the condition of cooling until the volume fraction of austenite in the above range became less than 0.1. In addition, calculations were performed assuming uniform and non-uniform cooling conditions, and the effects of non-uniform cooling conditions on the cross-sectional shape of the bloom and the stress generation behavior during the cooling were discussed.

The kinds of third cooling method analyzed in this study, were immersion cooling, in the case of static water, air stirring, and water jet stirring, spray cooling which is performed at a water density of 20, 50, 100 (l/(m²• min)) and mist-spray cooling which is performed at a water density of 20, 50(l/(m²• min)). The bloom surface is treated as a boundary of heat transfer and the heat transfer coefficients (H) in each cooling method and each cooling condition were estimated by the relationship between the surface temperature and H shown in Fig.2 (9)-(11). The heat transfer coefficients, which were measured for the upper surface or lower surface of steel bloom of rectangular cross section, used in the analyses of the case of mist-spray.

It's found that the H during immersion cooling is higher as the stirring is stronger, and H of water jet stirring is higher than that of spray cooling or mist cooling in a wide temperature range. H is increasing as increasing of water density in the case of spray and mist-spray cooling. At the same water density, H of mist-spray cooling at the lower surface of bloom is a little smaller than H of spray cooling at high temperature range. In the case of mist-spray cooling, H of upper surface of steel bloom is greater by the static water on the surface than H of lower surface in some temperature ranges.

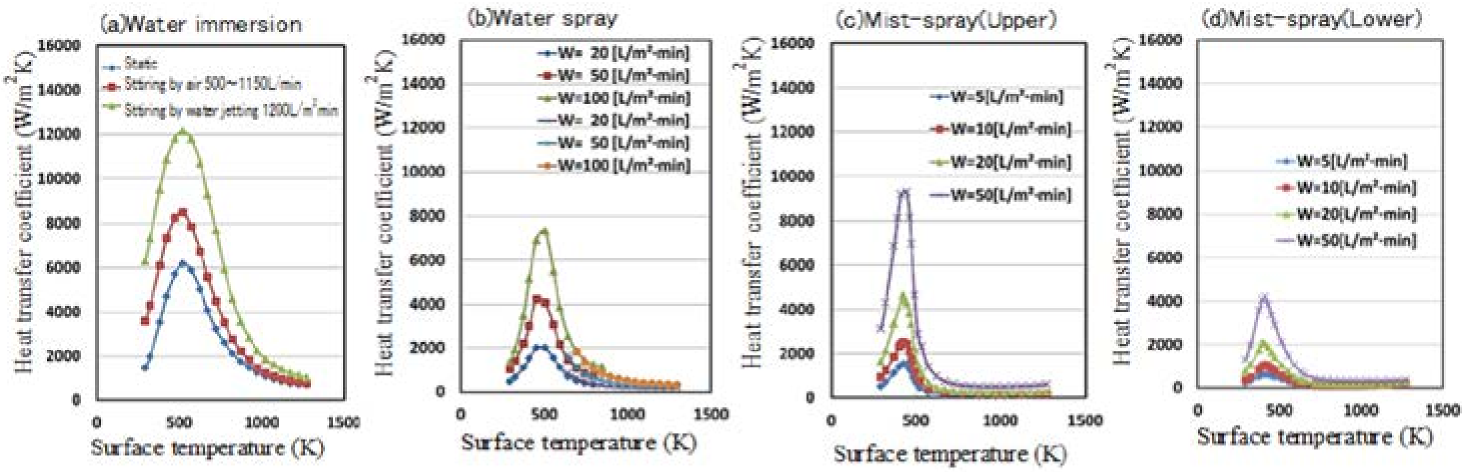


Fig.2 –Relations between surface temperature and heat transfer coefficients of immersion cooling, water spray cooling and mist-spray cooling (on upper surface and under surface).

Tab.1 - Analysis conditions in each case.

UNIFORM/NON-UNIFORM	COOLING METHOD	COOLING CONDITIONS (HEAT TRANSFER COEFFICIENTS)
Uniform Cooling	Immersion	Static water
		Air stiiring 500~1150(l/min)
		Water jet stirring W=1200 (l/(m²•min))
	Spray	W=20 (l/(m²•min))
		W=50 (l/(m²•min))
		W=100 (l/(m²•min))
	Mist-spray	W=20 (l/(m²•min)), Lower
		W=50 (l/(m²•min)), Lower

UNIFORM/NON-UNIFORM	COOLING METHOD	UPPER SURFACE	OTHER SURFACES
NON-Uniform Cooling	Immersion	Static water	Water jet stirring
	Spray	W=20 (l/(m²•min))	W=100 (l/(m²•min))
	Mist-spray	W=20(l/(m²•min)), Upper	W=20 (l/(m²•min)), Lower
		W=50(l/(m²•min)), Upper	W=50 (l/(m²•min)), Lower

RESULTS AND DISCUSSION

The cooling time required for the refinement of austenite grains in the surface layer of the bloom within a range of 10 mm by the reverse transformation treatment for various cooling methods and cooling conditions was clarified by the calculations. Fig. 3 is a bar graph showing the results of estimated the cooling time required for refining austenite grains. The required cooling time was determined as a time at which the volume fraction of austenite was 0.1 or less within a range of 10 mm from the surface of the bloom. As shown in this figure, the required cooling time decreased with the increase of the cooling strength together with the uniform cooling and the non-uniform cooling, and the required cooling time of the spray cooling was shorter than that of the mist-spray cooling, and the required cooling time of the immersion cooling was shorter than the spray cooling. In spray cooling or mist cooling, the required cooling time was shortened as the water density increased, and in immersion cooling, the heat transfer coefficient could be increased as the stirring intensity was increased, so that the required cooling time was shortened.

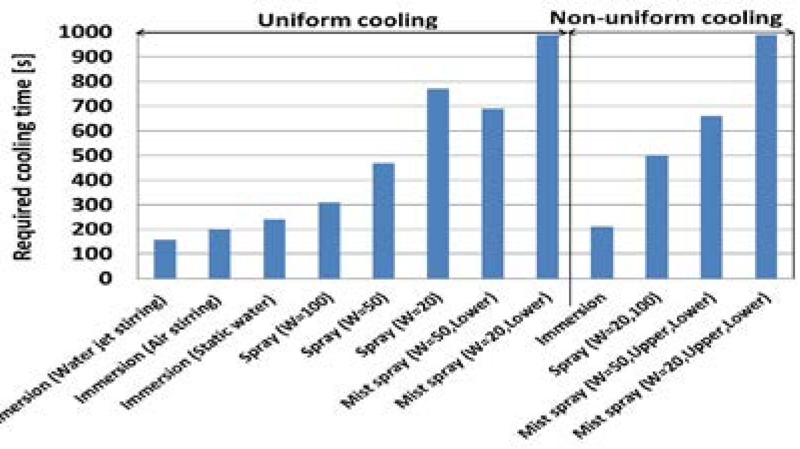
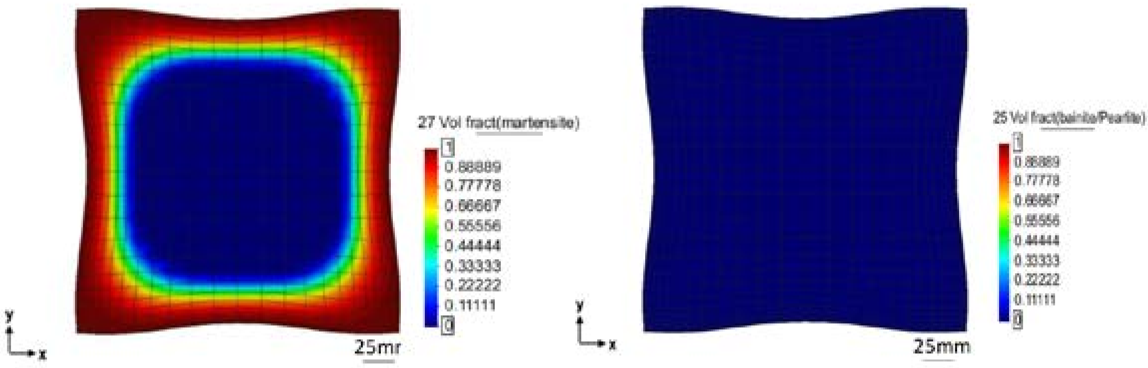


Fig.3 – Required cooling time for refinement of austenite grains of bloom surface region by reverse transformation treatment.

The effects of cooling methods and cooling conditions on the bloom cross-sectional shape at the end of cooling were studied using the model of metallo-thermo-mechanics. As examples, bloom cross-sectional shapes and contour diagrams of volume fraction of martensite and bainite and pearlite at end of cooling by uniform immersion cooling with water jet stirring and uniform mist-spray cooling with water volume density of 50 (l/(m²•min)) are shown in Fig.4, Fig.5. In the following figures of cross section of bloom, the total displacement is shown to be 40 times the actual value so that the effect of deformation by cooling can be more easily understood. Also, higher colors in the color bar correspond to higher values.

In the case of uniform immersion cooling, the heat transfer coefficient is larger in a wider temperature range than spray cooling and mist cooling. For the reason, the martensite generation rate in the case of immersion cooling relatively increased at the corners in the bloom cross section as shown in Fig. 4(a), so the shape of the bloom corner portion after cooling was changed to the shape protruding outward and the central portion of the surface was depressed. The bainitic and perlitic transformation didn't occur in this case(Fig.4(b)).On the other hand, in the case of mist-spray cooling (Fig.5), the amount of martensitic transformation was also larger at the corner side than at the center of the cross section, but the bainitic and perlitic transformation proceeded at the inside of the cross section during cooling, so that the expansion amount accompanying the transformation is large at the region, so the central part of surface of bloom had a swelling shape.



(a)Martensite volume fraction

(b) Bainite and pearlite volume fraction

Fig.4 – Cross-sectional shape of bloom and distribution of volume fraction of martensite, bainite and pearlite at the end of uniform immersion cooling. (Water jet stirring)

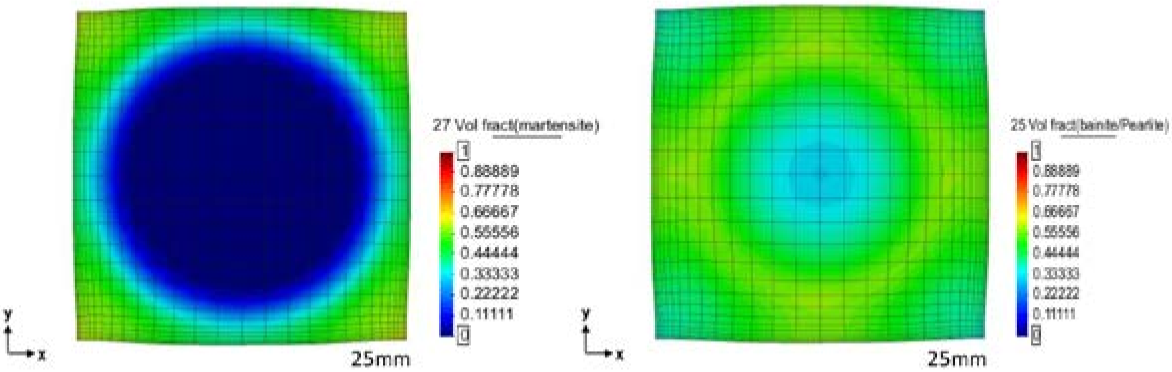


Fig.5 – Cross-sectional shape of bloom and distribution of volume fraction of martensite, bainite and pearlite at the end of uniform mist-spray cooling. (W=50 l/(m²• min)), lower))

The result of comparing the height difference of the surface of bloom at the end of cooling in the case of uniform cooling were discussed. From the result shown in Fig.6, it was found that the height difference of the upper surface in the several cases of uniform cooling is about 0.06 to 0.2 mm, and that the height difference of surface became larger as the cooling intensity increased with increasing power of stirring in the case of immersion cooling, and that the lower the water density of spray and mist-spray cooling, the slightly higher the height difference of bloom surface.

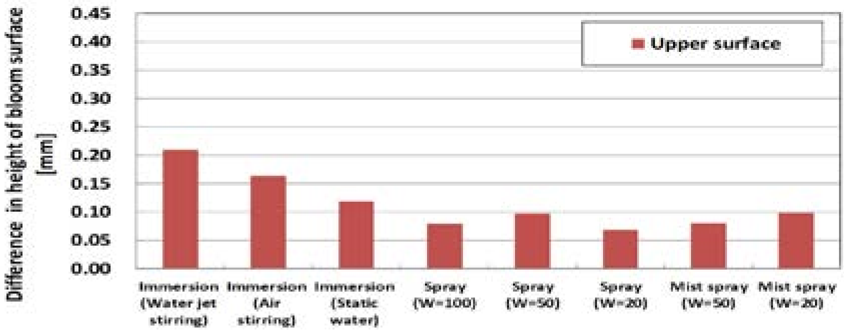


Fig.6 – Difference in height of surface of bloom at the end of uniform cooling by several kinds of cooling methods.

Fig. 7 and Fig.8 show the cross-sectional shapes of the bloom and contours of the volume fraction of martensite or bainite and pearlite at the end of non-uniform cooling. Fig. 7 shows the results in the case of non-uniform immersion cooling, and Fig. 8 shows the results in the case of non-uniform mist-spray cooling. In the case of immersion cooling (Fig.7), the heat transfer coefficient of static water was given only to the upper surface, and the heat transfer coefficient of water jet stirring was given to the other three surfaces. In addition, In the case of mist-spray cooling (Fig.8), the heat transfer coefficient of the upper surface at a water density of 20 (l /(m²•min)) was given only to the upper surface side, and the heat transfer coefficient of the lower surface at a water density of 20 (l /(m²•min)) was given to the other three surfaces.

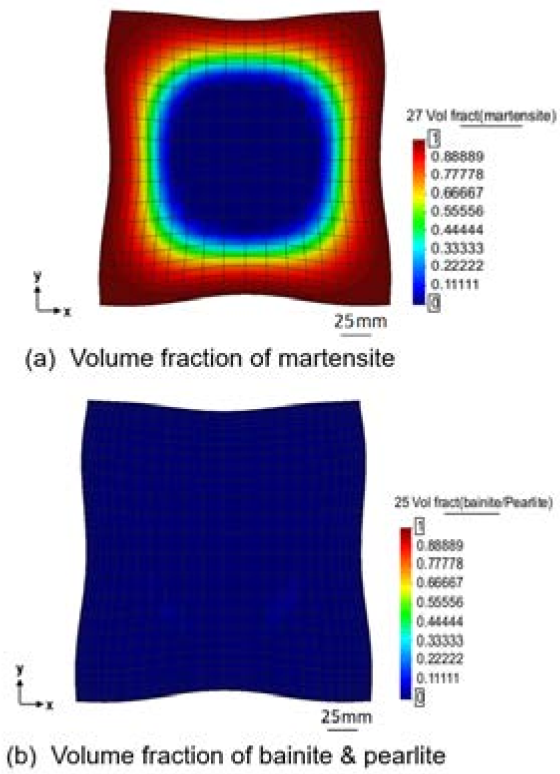


Fig.7 – Cross-sectional shape of bloom at the end of non-uniform immersion cooling. (Upper: Static water, Others: Water jet stirring)

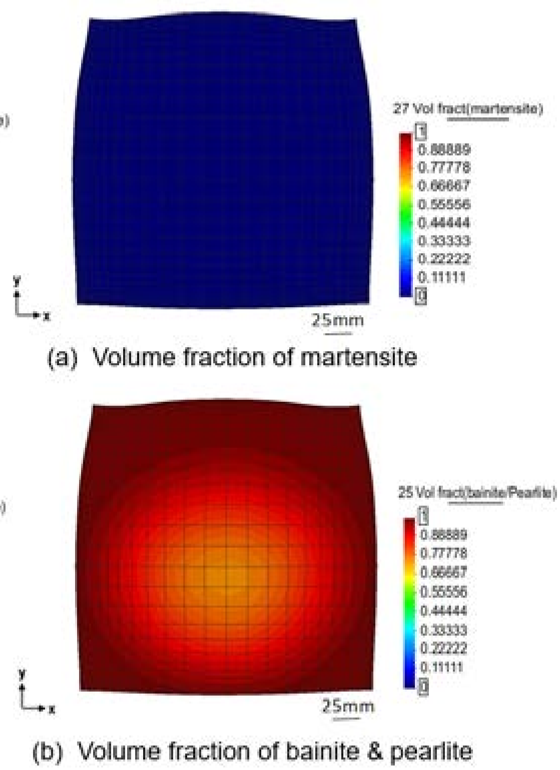


Fig.8 – Cross-sectional shape of bloom at the end of non-uniform mist-spray cooling. (Upper: W=20(l/(m²•min), Others: W=20 (l/ (m²•min)), lower)

In both the immersion cooling and the mist-spray cooling, it was found that the bloom width was reduced on the upper surface side as compared with the lower surface side. In the case of immersion cooling, the martensitic transformation amount and expansion amount of the transformation until the end of cooling do not show a large difference between the upper side and lower surface side, but the cooling strength on the upper surface side is lower and the temperature on the side of the bloom is higher than that of the lower surface side. Therefore, since the temperature transition was high and easily deformed, it was estimated that the bloom width was reduced on the upper surface side due to an increase in the amount of deformation due to thermal shrinkage of the upper surface during cooling.

On the other hand, in the case of non-uniform mist-spray cooling with a water density of 20 (l / (m^2 • min)), the amount of martensitic transformation is small on the both upper and lower surface side, and the amount of bainitic and pearlitic transformation and expansion amount of the transformation on the upper surface side are larger than the amounts on lower surface side. In spite of these quantitative relations, the width of bloom on upper surface region was reduced in comparison with the lower surface side, the decrease of the bloom width on the upper surface side was estimated to be due to the increased the amount of thermal shrinkage caused by the higher cooling strength on the upper surface side.

Fig. 9 is a bar graph showing the height difference on upper, lower and right surface of the bloom at the end of non-uniform cooling. Since the sides are deformed symmetrically, only the values on the right side are shown. In each case, the cooling intensity was changed on the upper surface side compared with the other surfaces, but in such cases, the height difference on the side surface was larger than the difference on other surface. The maximum value of the height difference of each surface was the maximum on the side where the water density was 20 (l/(m^2•min)) by mist cooling within the cases examined, and the maximum amount was about 0.4 mm at most. It was presumed that such a height difference of bloom surface is not significant in generating corner defects in blooming.

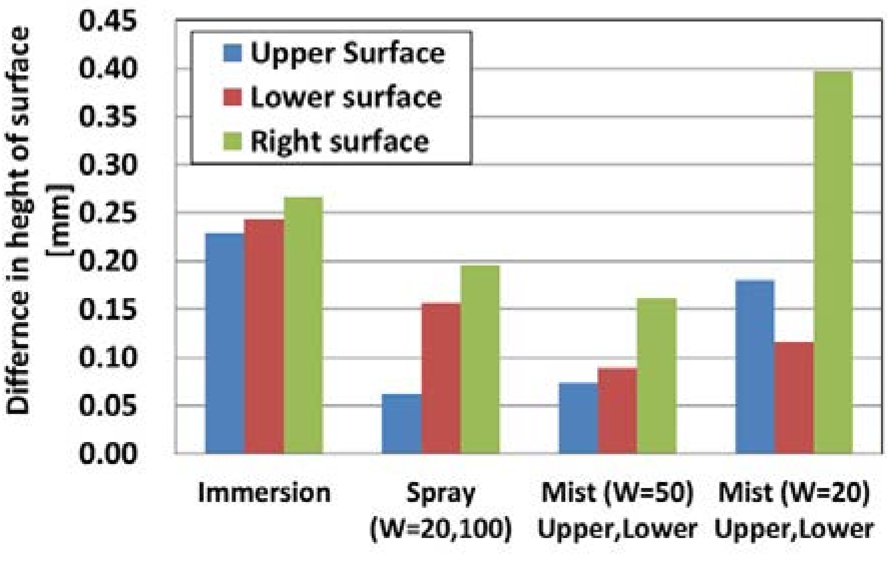


Fig.9 – Difference in height of surface of bloom at the end of cooling of several kinds of non-uniform cooling methods.

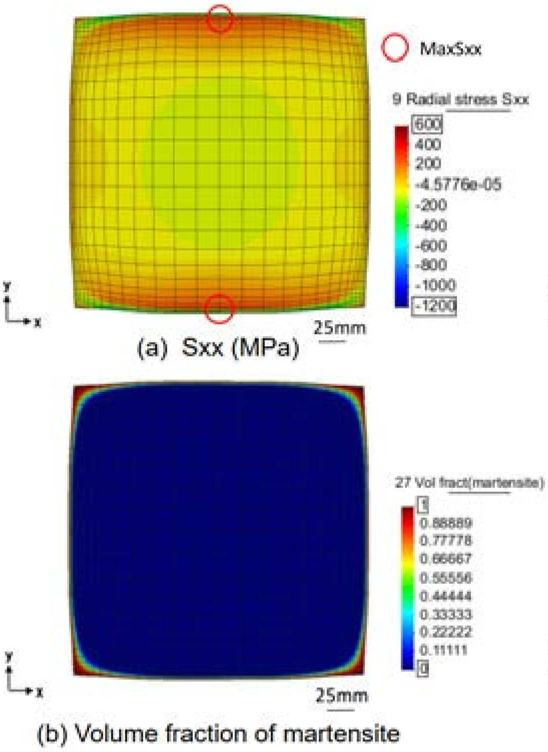


Fig.10 – Distribution of Sxx and volume fraction of martensite when Sxx is maximum during uniform immersion cooling. (Water jet stirring)

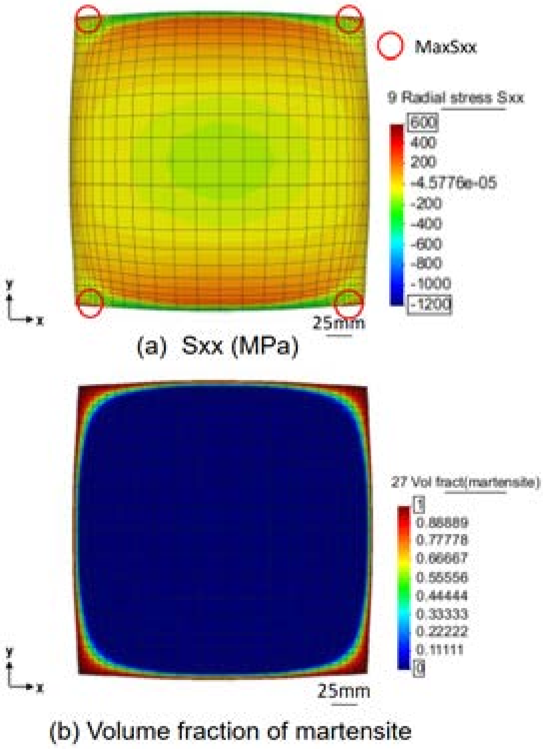


Fig.11 – Distribution of Sxx and volume fraction of martensite when Sxx is maximum during uniform immersion cooling. (Air stirring)

From the viewpoint of the prevention of the occurrence of quenching cracks, the behavior of stress generation in the cooling process by each cooling method was analyzed. Fig.10(a) and Fig.11(a) show the distributions of normal stress Sxx in the cross section of bloom in the case of uniform immersion cooling with water jet stirring and air stirring, when the stress Sxx during the cooling is maximum. Fig.10(b) and Fig.11(b) show the distributions of martensite volume fraction in the cross section at that time. The Sxx became maximum in the position indicated by the circle. In these cases of uniform immersion cooling, the amount generated bainite and pearlite phase is very small, and it is considered that the transformation expansion due to martensitic transformation near the surface of bloom and thermal stress cause the generation of maximum Sxx in these cases. In the case of immersion cooling with water jet stirring (Fig.10), the Sxx became maximum in the austenitic phase region just below the surface at the center of the surface. It was seemed that the stress Sxx became the maximum just below the center of the surface, because the austenitic phase region just below the surface at the width center was pulled in the bloom width direction by the expansion due to martensitic transformation at the surrounding surface. On the other hand, in the case of immersion cooling with air stirring (Fig.11), the surface layer at the off-corner was pulled in the bloom width direction due to the progress of martensitic transformation inside the cross section of the corner. It is considered that the maximum stress Sxx occurred at the position, because of the martensitic transformation, the effect of thermal shrinkage and the large deformation resistance at the region caused by the low temperature.

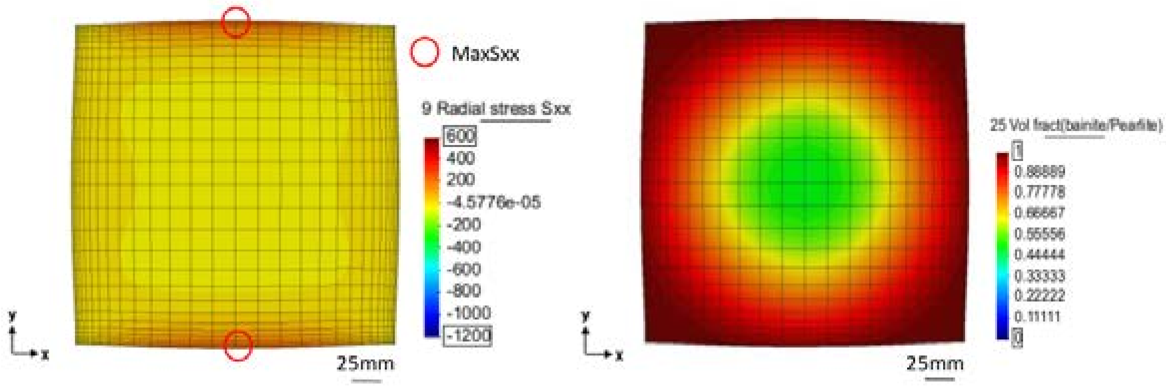


Fig.12 – Distribution of Sxx and volume fraction of bainite and pearlite when Sxx is maximum during uniform mist-spray cooling. (H: W=20 (l/(m²• min)), lower)

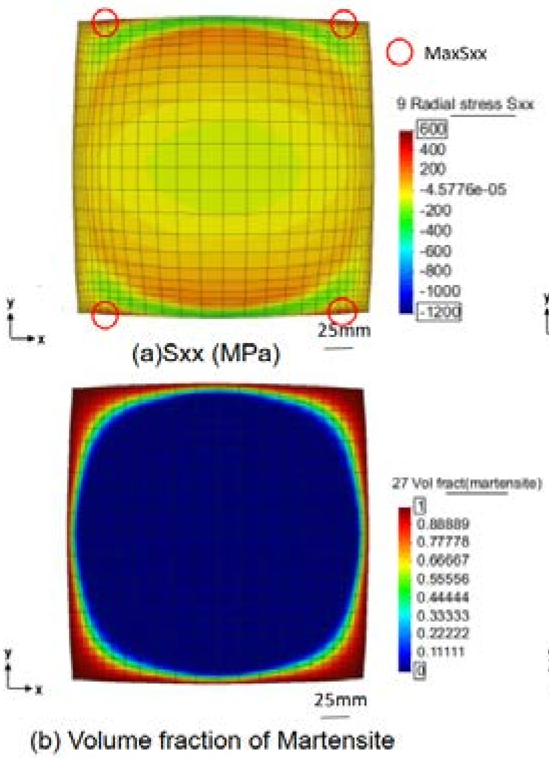


Fig.13 – Distribution of Sxx and volume fraction of martensite when Sxx is maximum during uniform spray cooling. (W=100 (l/(m²• min)))

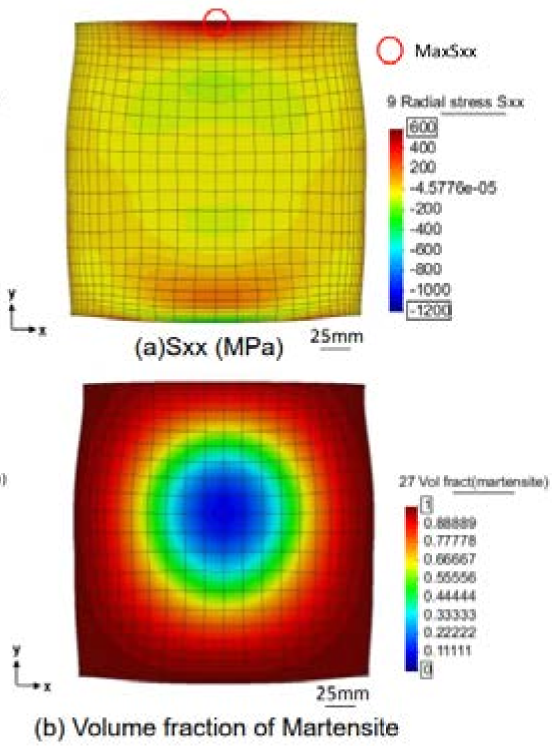


Fig.14 – Distribution of Sxx and volume fraction of martensite when Sxx is maximum during non-uniform spray cooling. (Upper: W=20 (l/(m²• min), Lower, Side: W=100 (l/(m²• min))

Fig. 12 shows the distribution of Sxx when the maximum Sxx occurs and the distribution of bainite and pearlite volume fraction in the case of uniform mist-spray cooling with the water density of 20 (l/(m² • min)), the weakest cooling intensity. From the analysis for this case, it can be seen that in this case, martensitic transformation does not undergo during the cooling and bainitic and pearlitic transformation occurs over a large area of the cross section. As a result, it was found that the expansion due to these transformations expanded the upper and lower surface layers and increased Sxx at the surface.

When the water density on the bloom upper surface side is 20 (l/(m²• min)), and the other three surfaces are cooled by spray at 100 (l/(m²• min)), distribution of Sxx and martensite volume fraction in the cross section of bloom are shown in Fig.14 in comparison with the case of cooling uniformly on all four sides with water density of 100 (l/(m²• min))(Fig.13). In the case of uniform spray cooling with 100 (l/(m²• min) shown in Fig.13, the maximum Sxx occurred on the off-corner surface due to expansion accompanying martensitic transformation at inside near the corner. In the non-uniform spray cooling (Fig.14), the upper surface layer whose temperature is higher than the other three surface layers is pulled due to martensitic transformation inside the cross section and the thermal shrinkage caused by constraint from the side surface of which temperature is lower. For the above reasons, it was found that the largest Sxx occurred at the center of the width of the upper surface in this case.

Compared with uniform cooling, in non-uniform cooling, the position, timing, and mechanism at which the maximum Sxx occurs differ greatly, and the maximum Sxx greatly increased in the case of non-uniform cooling with strong cooling intensity.

The maximum Sxx during cooling in various cooling methods and conditions is shown in the bar graph of Fig.15. In the uniform immersion cooling, the maximum Sxx was almost constant regardless of the stirring power of the immersion bath. In the uniform cooling with spray and mist-spray, Sxx decreased as the water density decreased. In this study, in spray cooling and mist cooling, there are some cases where non-uniform cooling significantly increased the maximum Sxx in comparison with uniform cooling.

From the results shown in this figure, it was found that spray cooling or mist cooling at a low water density of about 20 (l/(m²• min)) was preferable to reduce the stress of Sxx etc. It was estimated that it was important for decrease of stress and prevention of quenching crack occurrence to reduce the variation in cooling strength between surfaces of bloom.

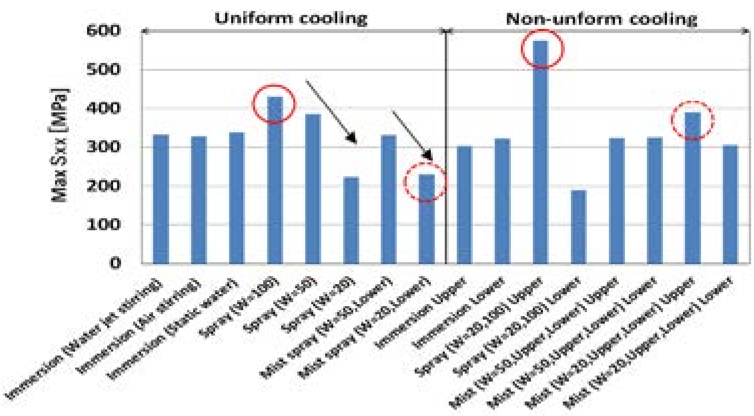


Fig.15 – Max Sxx in the case of each cooling method and each cooling condition.

SAMMARY AND CONCLUSION

In this study, the causes of thermal distortion and quenching crack and the effects of kinds of cooling methods and cooling conditions in the reverse transformation treatment were analyzed in order to prevent these troubles by the model of metallo-thermo-mechanics. The cooling methods considered in these analyses were immersion cooling, spray cooling and mist-spray cooling. The following results were obtained from these analyses.

1) In several kinds of cooling methods (immersion cooling, spray cooling and mist-spray cooling) and various cooling conditions, the cooling time required for the reverse transformation treatment were clarified.

2) The effects of the cooling methods and various cooling conditions on the cross-sectional shape of the cast bloom after cooling and the stress generated during co-

oling were analyzed from the viewpoint of the behavior of martensitic, bainitic and pearlitic transformation and the expansion accompanied with these transformation and thermal shrinkage behavior.

In addition, the following findings were obtained regarding the cooling method and cooling conditions.

3) From the viewpoint of shortening the required cooling time, immersion cooling is advantageous.

4) The difference in the effect of the cooling methods and the cooling conditions on the cross-sectional shape of the bloom after cooling is small.

5) From the viewpoint of preventing the occurrence of quenching cracks, it was revealed that it was necessary to reduce the variation in cooling strength on the outer surface and to use spray or mist-spray cooling with a significantly reduced water density as a cooling method.

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