# Cracking Mechanism of High Carbon Slab after Machine Scarfing

**MING-HUNG CHEN, KUAN-JU LIN, KAI-LIANG HUANG and CHING-CHAO YANG**

*Steel and Aluminum Research and Development Department*
*China Steel Corporation*
*Hsiao Kang, Kaohsiung 81233, Taiwan, R.O.C.*

**JIS SK85 high carbon steel is a newly-developed high-grade product in China Steel. In the early production period, the slab was occasionally found to break during hot rolling process, which severely influenced the production. It was found after the process investigation that the broken slabs were caused by time-delayed cracks in the slab after machine scarfing. A numerical simulation revealed that the time-delayed cracks were caused by a hard, brittle martensite layer in the slab surface together with a tensile residual stress induced by the compressive thermal stress after machine scarfing. The formation of the martensite layer could be avoided by maintaining the slab temperature higher than 200°C. And the time-delayed cracking on the scarfed surface could be completely prevented if the slab temperature was increased to 400 °C.**

## 1. INTRODUCTION

The Research & Development have been devoted for decades to developing steels of high quality and to generating high grade products to meet the customer's requirements. One of these newly-developed grades was JIS SK85 high carbon tool steel with 0.85% C content. In the early period, the SK85 slab was occasionally found to break during the hot rolling process, as shown in Fig. 1, which severely influenced production. Then, a severer concern was that the SK85 slabs might break in the furnace and cause the breakdown of the whole hot rolling line for weeks since the fallen mass of broken slab might jam the continuous feeding of slab into the furnace. As a result, all SK85 slabs were temporarily rejected by the rolling shop until the problem was thoroughly solved. Therefore many investigations were carried out to find the mechanism of the slab breaking in the hot rolling process. Finally, it was found that the main cause was the improper application of the machine scarfing process.

During continuous casting, some abnormal process conditions may cause the mold powder, air bubbles or the inclusion clusters to be caught in the solidifying shell, for example by a large mold level fluctuation, or an excessive argon flow rate. The surface quality of the slab therefore becomes deteriorated and provokes a quality problem in the downstream hot rolling process. As a result, the slab is sent for machine scarfing as the process parameters of the continuous casting exceed the control limit. An approximate layer of 2 mm thickness on each wide surface of slab is removed by machine scarfing to improve the quality of slab. Machine scarfing is a very useful and efficient process to improve the surface quality of slab as compared to machine grinding. However, very few literatures about the machine scarfing are reported and the influence of machine scarfing on the slab is still not clear. Consequently a foundation study of machine scarfing needed to be performed. Subject to the physical limitations of on-line measurement, a numerical model was employed to simulate the temperature and the thermal stress

**Fig. 1.** Appearance of broken SK85 slab during hot rolling process.

variation and also the microstructure evolution in the slab during machine scarfing.

## 2. EXPERIMENTIAL PROCEDURE

A simplified two-dimension slab geometry and a torch model of machine scarfing were proposed in the calculation, as shown in Fig. 2 (a). The slab thickness was 265 mm and the slab length was reduced to 2,000 mm since the thermal variation was steady as the length exceeded 2,000 mm. The cooling effect of air convection and radiation were taken into account, but the cooling water was neglected. A quadratic element was used to calculate the model and a criterion was set to the quadratic element to avoid the interference with the temperature calculation on the surface. The element was removed spontaneously as the average temperature of all nodes in an element exceeded the solidus (1,380 °C). The simulation was performed by a commercial code MARC.

The slab was stationary and the torch was movable, which was contrary to the real process. The torch was simplified to a heat flux input of unit function form. The width of torch was 50 mm ($\Delta x$) and the initial position ($x_{pre}$) was 180 mm from the left end of slab. In the preheating stage, the torch was fixed and preheated the slab for 44 seconds with a constant heat flux input ($Q_{pre}$). Then the torch began to move with a constant speed of 7.6 m/min to scarf the slab and the heat flux input changed rapidly to a higher value ($Q_{sca}$), as indicated in the Fig. 2 (b). The values of the heat flux input were obtained by trial and error with an assumption of removed thickness near to 2 mm. The initial temperature of slab was assumed to be uniformly 30°C, 200°C, 400°C and 800°C while the heat flux input was kept the same. The initial conditions and boundary conditions of torch are summarized below,

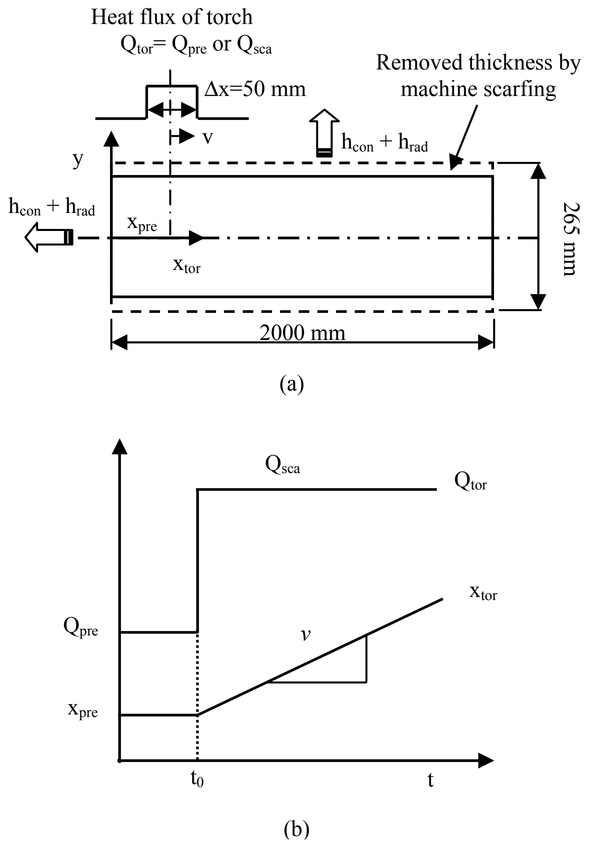



**Fig. 2.** (a) Simple thermal model of machine scarfing; and (b) the relation between the position and heat flux of torch.

$$x_{tor} = x_{pre} = 180\ mm, \text{ when } t \le t_0 \quad \text{(1a)}$$

$$x_{tor} = x_{pre} + v\,(t - t_0), \text{ when } t > t_0 \quad \text{(1b)}$$

$$v = 7.6 \text{ m/min} \quad \text{(2)}$$

$$Q_{in} = Q_{tor} \text{ if } |x - x_{tor}| \le \Delta x/2,\ \Delta x = 50 \text{ mm} \quad \text{(3a)}$$

$$Q_{in} = 0 \text{ if } |x - x_{tor}| > \Delta x/2 \quad \text{(3b)}$$

$$Q_{tor} = Q_{pre}, \text{ when } t \le t_0 = 44\ sec \quad \text{(4a)}$$

$$Q_{tor} = Q_{sca}, \text{ when } t > t_0 \quad \text{(4b)}$$

## 3. RESULTS AND DISCUSSION

### *3.1 Investigations of Slab Cracking During Hot Rolling*

A systematic investigation was carried out in order to solve the problem of slab cracking under hot rolling. A chemical composition check, mechanical tests at high temperature, microstructure analysis of the broken slab, process parameter tracing, and the thermal history and slab conditioning of the broken slab were all investigated, including the hot rolling process.[1-3] Moreover, a trial test of slab machine scarfing was carried out in order to verify the cracking phenomenon, as shown in Fig. 3. The pattern of the cracks on the trial scarfed slab was very similar to those on the broken slabs, especially the continuous transverse crack along the preheating zone. The cracks evidently appeared after machine scarfing and a penetration test revealed that the maximum crack width reached 1mm. According to the experimental record, the cracks started to form 24 hours after machine scarfing. This delayed crack propagation was the reason why the severely cracked slabs could pass the on-line manual inspection and be delivered to the downstream shop. The surface microstructure of scarfed slab was examined and found to be composed of martensite. There should be a compressive stress existing in this martensite layer induced by the phase transformation from austensite. A more comprehensive knowledge has to be acquired to explain the cracking mechanism.

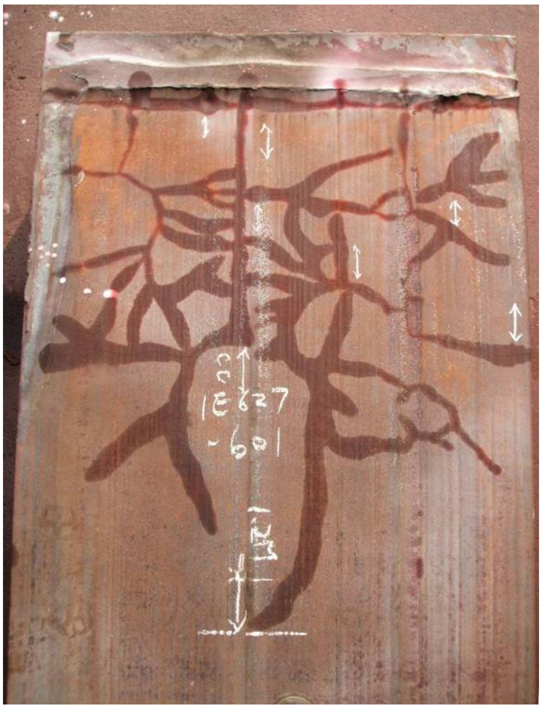



**Fig. 3.** Penetration test of SK85 slab after machine scarfing.

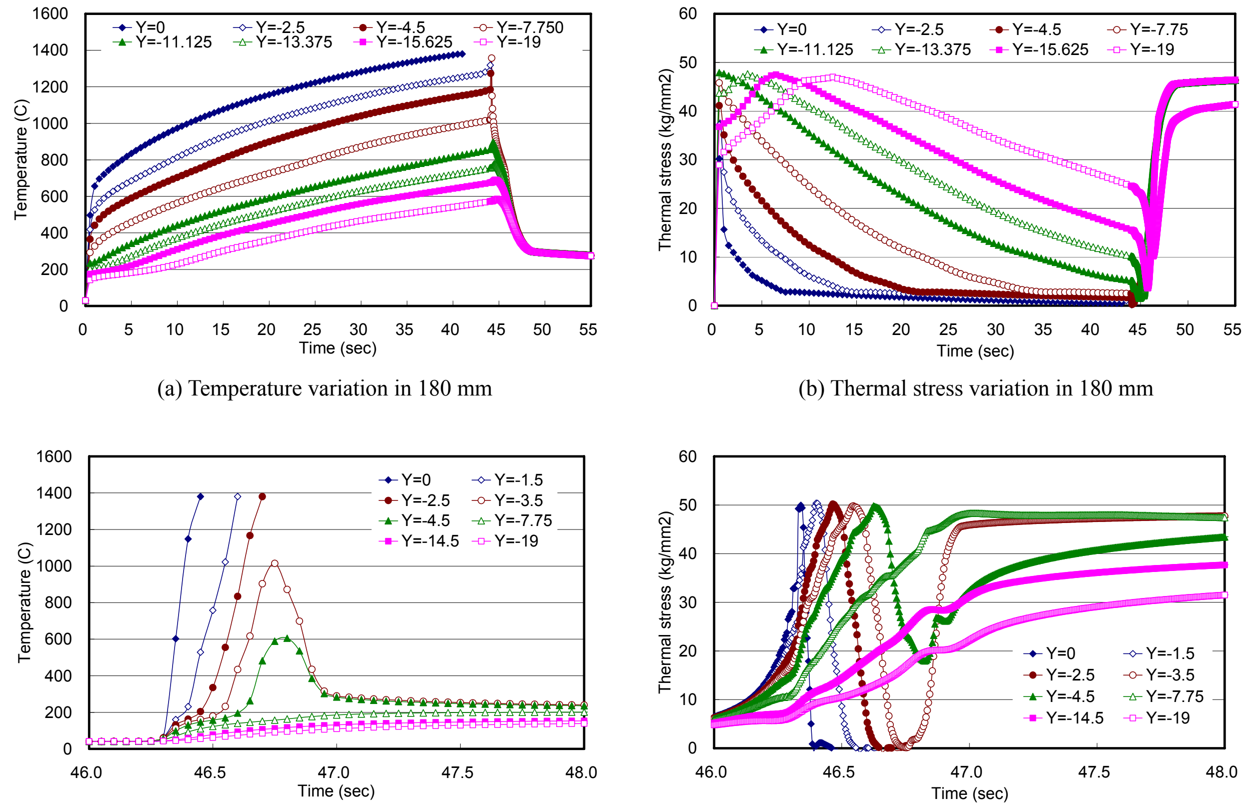
### *3.2 Temperature and Stress Variations During Machine Scarfing*

After several trials at different temperature, the two values of heat flux input for preheating and for scarfing were determined and the removed thicknesses are listed in Table 1. The initial temperature of slab was assumed to be 30°C uniformly for a general cold slab. The results show that the temperature in the slab surface initially increased rapidly as the torch heated the slab and then slowly as the temperature exceeded 723°C approximately during the preheating stage as shown in Fig. 4 (a). The temperature profile was contributed mainly by the thermal properties of SK85 at various temperatures, i.e. Cp (Specific heat capacity at constant pressure) and K (Thermal conductibility) values. Correspondingly the compressive thermal stress also increased rapidly in the initial stage, but after reaching a maximum it began to decrease due to the material softness at high temperature; moreover, the position of maximum thermal stress was getting deeper and deeper as the time increased, as shown in Fig. 4 (b). The mechanical properties of SK85 at different temperatures are illustrated in Fig. 5.

However, Fig. 4 (b) also shows that the compressive thermal stress rose again and reached the yielding strength as the torch started to move from the preheating zone (after 44 seconds) and the slab surface was cooled by the inner cold part. The thermal stress kept constant after it reached the yielding strength since an elastic-perfect plastic model was adopted in the calculation. A similar variation of temperature and thermal stress was also observed in the steady scarfing stage as shown in Fig. 4 (c) and Fig. 4 (d). As the compressive thermal stress exceeded the yielding strength, a plastic deformation occurred and an inverse tensile residual stress was therefore induced after the thermal stress was released. A detailed distribution of the temperature and the thermal stress in the slab at 46 seconds after machine scarfing is shown in Fig. 6. A thick and deep thermal stress distribution was shown in the preheating zone while a thinner and shallower one was shown in the steady scarfing zone. The residual stress distribution could be presumed to be similar to the thermal stress distribution as the slab temperature cooled down. Moreover, the residual stress distribution could provide a reasonable explanation for the cracking

**Table 1 Comparison of Removed Depth, Austenitized Depth and Microstructure Evolution of SK85 Slab at Different Temperatures after Machine Scarfing**

| Position | Temperature / Thickness | 30°C | 200°C | 400°C | 800°C |
|---|---|---|---|---|---|
| Center of preheating zone (180 mm from the end) | Removed depth | 6.6 mm | 6.6 mm | 7.8 mm | 10.0 mm |
| | Austenitized depth | 5.6 mm | 7.9 mm | 10.1 mm | Full thickness |
| | Hardened layer | 3.4 mm (Martensite) | None | None | None |
| Scarfing zone with constant speed (500 mm from the end) | Removed depth | 2.5 mm | 2.5 mm | 2.5 mm | 4.5 mm |
| | Austenitized depth | 1.0 mm | 2.0 mm | 2.0 mm | Full thickness |
| | Hardened layer | 1.0 mm (Martensite) | 2.0 mm (Bainite) | 2.0 mm (Bainite) | None |




(a) Temperature variation in 180 mm (b) Thermal stress variation in 180 mm

(c) Temperature variation in 500 mm (d) Thermal stress variation in 500 mm

**Fig. 4.** Temperature and thermal stress variations of SK85 slab during machine scarfing in preheating zone (180 mm from end) and steady scarfing zone (500 mm from end). The initial temperature of slab was 30°C uniformly.

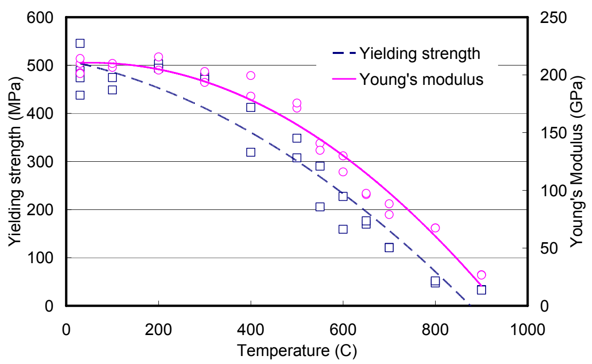



**Fig. 5.** Mechanical properties of SK85 steel at different temperatures.

mechanism of the slab. As mentioned previously, a large volume of tensile residual stress existed in the preheating zone, and a thin and shallower volume of tensile residual stress existed in the steady scarfing zone. A higher force magnitude of tensile residual stress in the preheating zone was expected and initiated cracks on the scarfed slab, which agreed with the experimental observation. Even a compressive residual stress induced by a martensite transformation could be completely balanced by the tensile residual stress.

Scarfing a cold slab induced a large amount of tensile residual stress on the scarfed surface. If the slab temperature was increased, then the magnitude of the thermal stress was gradually reduced, as shown in Fig. 6. The magnitude of the difference in thermal stress between 30°C and 200°C was small since the Young's modulus was similar, as illustrated in Fig. 5. As the slab temperature became higher than 400°C, the thermal stress exhibited a significant decrease; however, the yielding strength also decreased at the higher temperatures, so the thermal stress still exceeded the yielding strength even at 400°C. Moreover a high slab temperature was very beneficial to release the residual stress caused by the thermal stress, especially when the temperature was higher than 300°C. There is usually a better ductility at higher temperatures, which provides a larger tolerance to bear the thermal elastic deformation and results in a decrease of thermal plastic deformation. Thus the residual stress caused by the thermal stress was reduced at higher temperatures. It was therefore suggested that, for a brittle steel, it is better to scarf the slab at a temperature higher than 400°C in order to prevent the cracking.

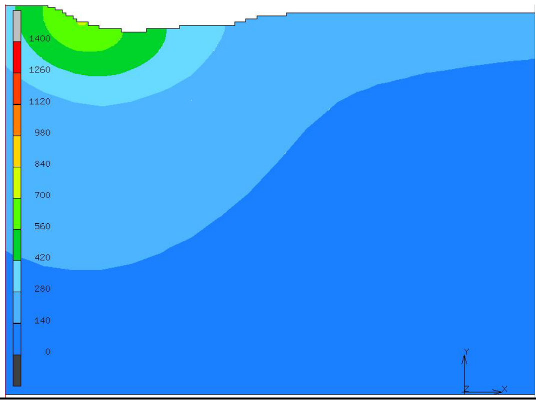
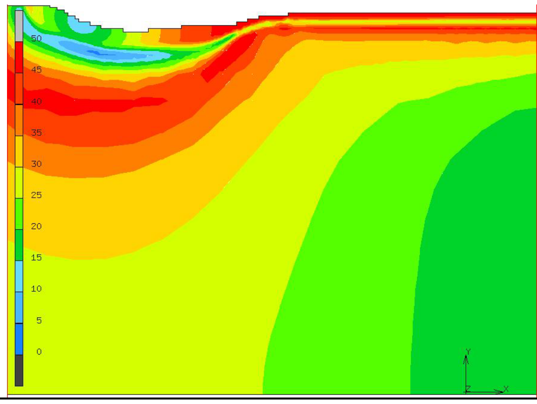
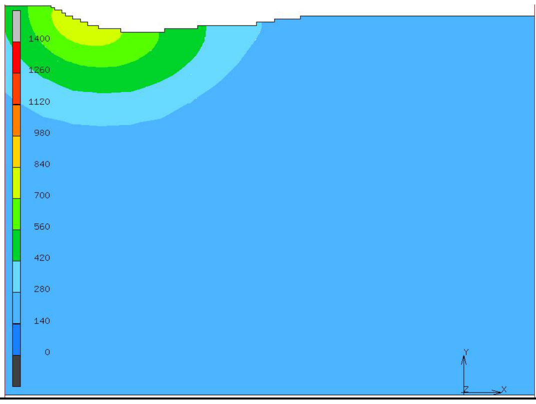
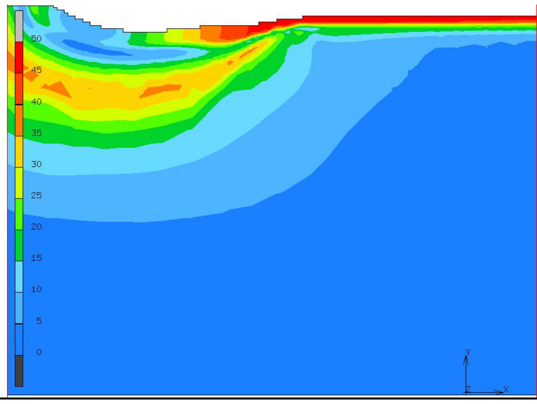
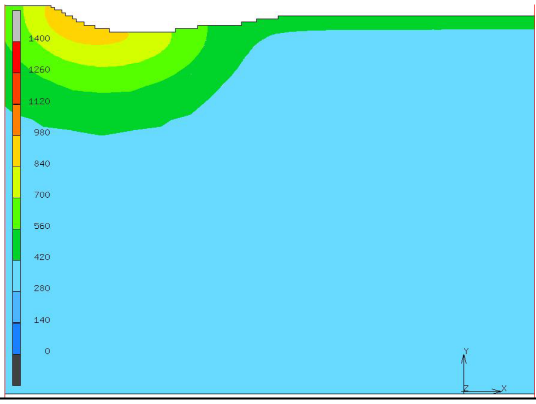
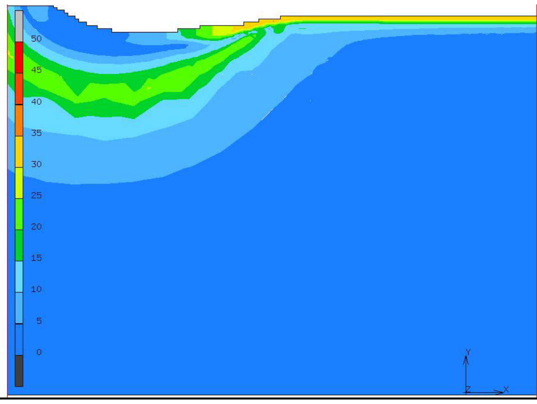
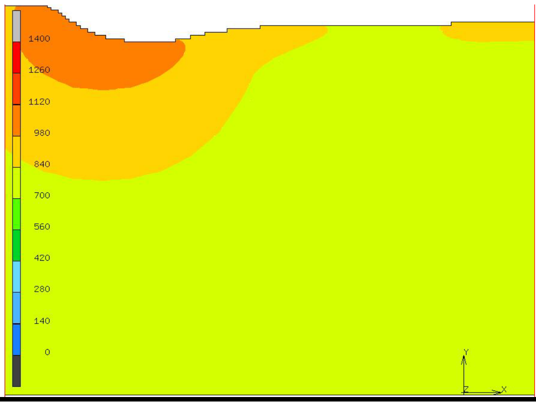
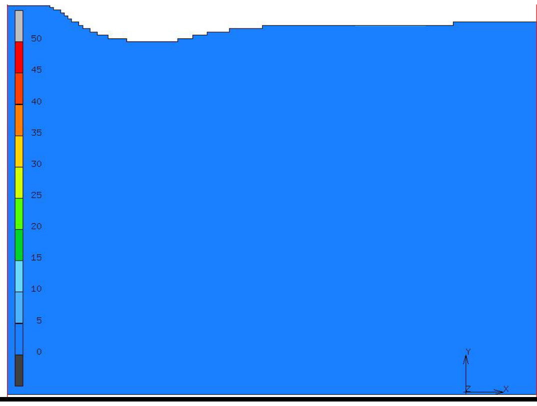
| | Slab temperature distribution | Thermal stress distribution |
|---|---|---|
| Slab temp. 30℃ |  |  |
| Slab temp. 200℃ |  |  |
| Slab temp. 400℃ |  |  |
| Slab temp. 800℃ |  |  |

**Fig. 6.** Distributions of temperature and thermal stress in the SK85 slab at 46 seconds after machine scarfing.

### *3.3 Phase Transformation During Machine Scarfing*

SK85 is a carbon tool steel with a high hardenability due to its chemical composition. A martensite layer could be found in the scarfed surface for a cold slab as shown in Fig. 7. This martensite layer was very brittle and exhibited a low fracture toughness. As the slab surface was subjected to a large tensile residual stress, the martensite layer was prone to crack. Therefore the prevention of the formation of a martensite layer in the scarfed surface was very important to avoid the cracks after machine scarfing.

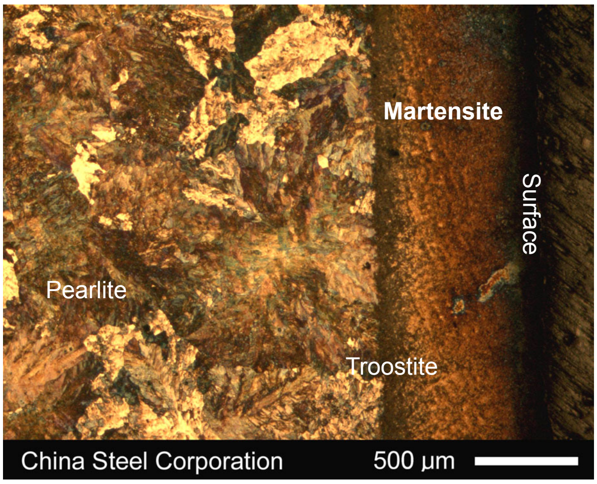



**Fig. 7.** Surface microstructures of SK85 slab after machine scarfing.

The thermal histories in any position of slab during machine scarfing were obtained from the calculation results of the thermal model in the previous section. As the chemical composition of SK85 was very close to the eutectoid, a CCT (Continuous cooling transformation) diagram of eutectoid steel was used for microstructure prediction. A critical cooling rate of martensite transformation of 140°C/sec was obtained from the diagram. The simulation results are summarized in Table 1, which was verified by experimental evidence. A section of cold SK85 slab was scarfed and macro-etched longitudinally as shown in Fig. 8. The thickness of the hardened layer was almost equivalent to the simulation results, which validated the accuracy of simulation.

It was found that the surface microstructure of SK85 transformed to a tough and hard bainite phase in the steady scarfing zone and no transformation occurred in the preheating zone as the slab temperature was higher than 200°C. The hardened layer was eliminated completely as the slab temperature reached 800°C. However, it was effective to increase the slab temperature just higher than 200°C to eliminate the formation of the martensite phase.

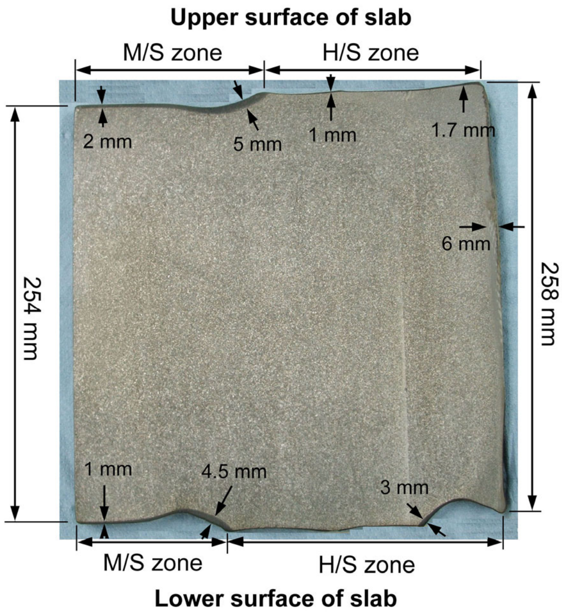



**Fig. 8.** Macro-etched structure of longitudinal section of SK85 slab in the end part, which was processed by a machine scarfing (M/S) and a hand scarfing (H/S).

## 4. CONCLUSIONS

SK85 is a carbon tool steel with a high hardenability. A hard and brittle martensite layer was found in the scarfed slab surface after machine scarfing. Severe time-delayed cracking occurred in the scarfed surface and resulted in breakage during the hot rolling process. The calculation results showed that there was a large amount of compressive thermal stress induced after machine scarfing and this resulted in tensile residual stress on the scarfed surface. The time-delayed cracking was caused by the tensile residual stress and the brittle martensite layer on the scarfed surface. Further study showed that the time-delayed cracking on the scarfed surface could be prevented when the initial slab temperature was increased to 400°C.

## REFERENCES

1. M. H. Chen and et al., China Steel Corp. Internal Technical Report, TS94073, 2005.
2. C. Y. Chang and et al., China Steel Corp. Internal Technical Report, S-94-022, 2005.
3. M. H. Chen, K. J. Lin, C. C. Yang and K. L. Huang: Mining & Metallurgy, vol. 52, No. 3, 2008, pp. 107-112.