

Chapter 4

Phase Transformation and Residual Stresses

4.1 Critical Grinding Conditions

When workmaterial experiences a critical temperature change in grinding, phase transformation will take place. For the given workmaterial properties of EN23 steel, at the austenising temperature, 850°C, the workpiece surface undergoes phase change to an austenite phase. If cooling happens after that, another phase change can take place depending on the cooling rate. For EN23, the critical cooling rate is identified by the critical time required to lower the grinding temperature from 750 °C to 500 °C as calculated by eq. (2.18). Under a slow cooling rate (cooling time above 1.6 sec), the phase change can still take place, but the change of mechanical and thermal properties anticipated would be minor. Therefore, it is reasonable to assume that the workmaterial properties associated with a low cooling rate do not change.

As shown in Fig. 4.1, there exist a wide range of grinding conditions that can initiate a martensite phase particularly when the wheel-workpiece contact length (or the length of grinding zone), L_c , is small. For $L_c = 2$ mm, which is used throughout this study, the minimum Peclet number required to initiate the phase transformation is very small and in the order of 0.015 which in turn corresponds to a very low table speed. Therefore it is sufficient to bring the grinding temperature above an austenising temperature in order for the phase change to take place. Figure 4.2 reveals the onset of martensite transformation in relation to heat flux intensity, q_a . It is obvious that a higher convection heat transfer coefficient increases the input heat flux required to initiate the phase transformation. The critical input heat flux intensity is changing rapidly at a lower Peclet number. At higher Peclet numbers, however, the change can be considered as linear in terms of Peclet number.

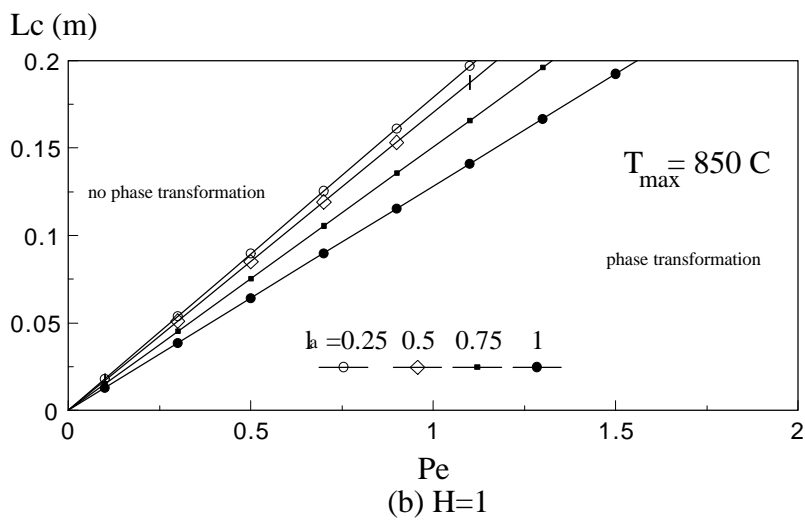
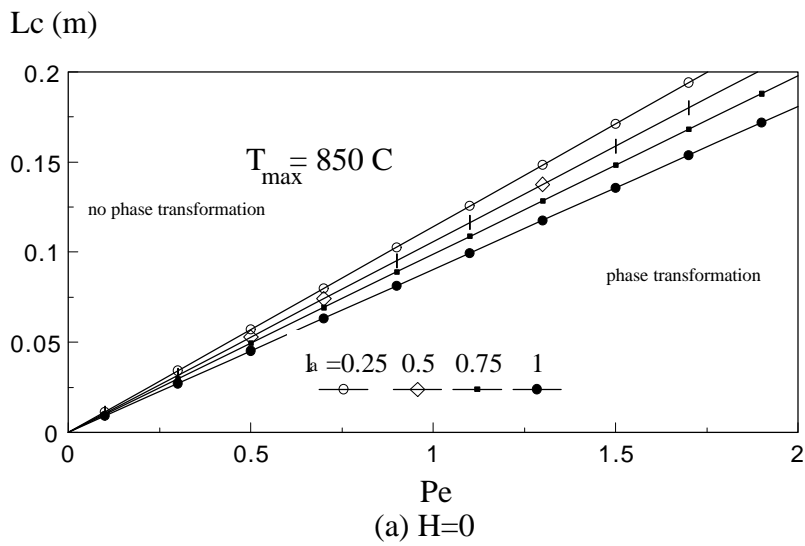


Figure 4.1 Critical grinding conditions for onset of phase transformation

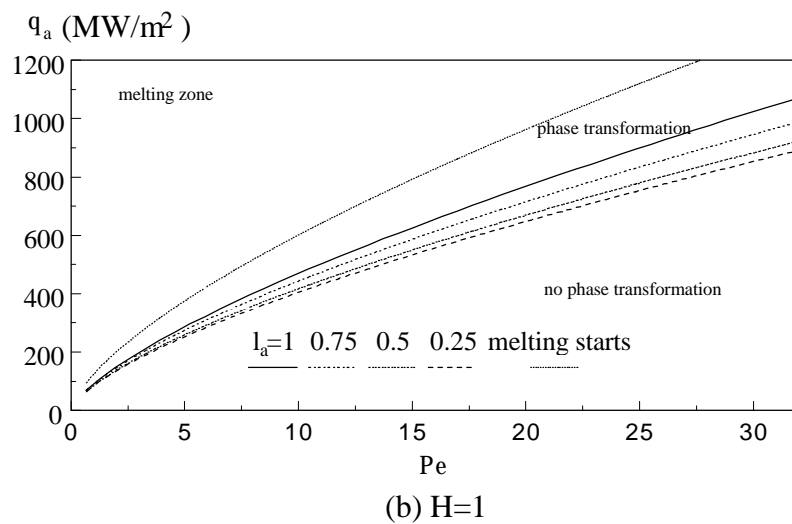
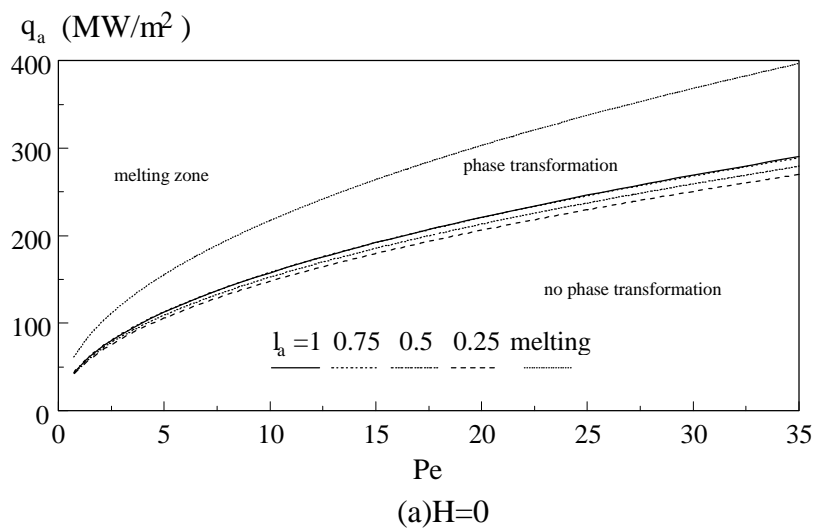


Figure 4.2 Critical conditions of transformation ($l_a=0.25$, $L_c = 2\text{mm}$)

4.2 Martensite Depth

As a workpiece experiences a critical grinding temperature history, martensite transformation occurs. However, since heat source and convection are on the surface, different parts of the workpiece material must experience a different heating and cooling history. It is therefore understandable that at a certain depth in the subsurface, heating and cooling cannot activate phase transformation even though it does take place near the surface. The depth of the layer with martensite transformation must therefore be a function of material properties of the workpiece and grinding conditions, including table speed, depth of cut, cooling rate and so on.

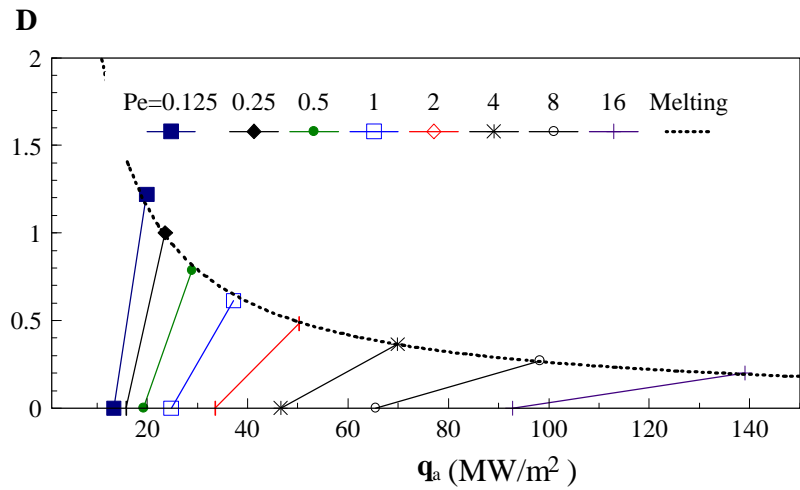
Figure 4.3 demonstrates the variation of the martensite depth with the input heat flux intensity, q_a , and the Peclet number, Pe . It shows that the martensite depth is strongly but linearly dependent on q_a when Pe is low. This is attributed to the linear variation of the maximum grinding temperature in the subsurface of the workpiece. Cooling has a remarkable effect on reducing the martensite depth by lowering the grinding temperature. The type of grinding mechanism, with different l_a , has little influence on the martensite depth since grinding type affects temperature only slightly. For example, an up-grinding process (e.g. $l_a=0.25$) results in a slightly larger martensite depth than that induced by a down grinding (e.g. $l_a=0.75$) if all other conditions are the same.

4.3 Residual Stress Distribution

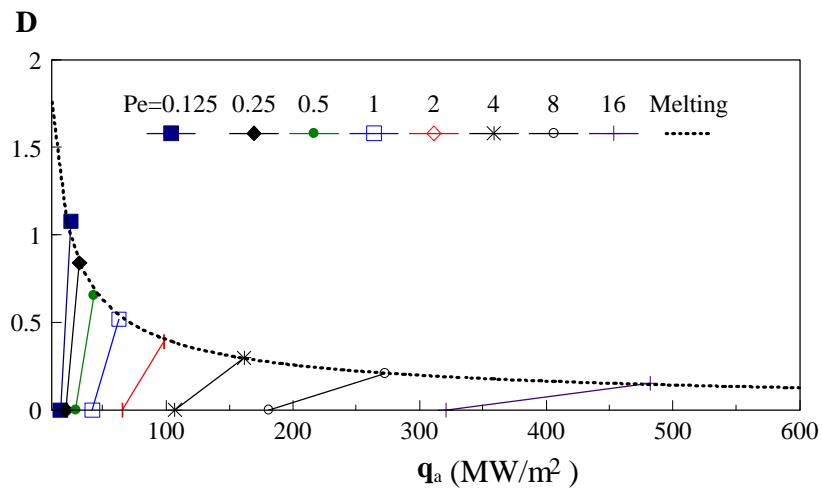
4.3.1 Effect of Phase Transformation

The change of workmaterial properties associated with phase change plays a major role in residual stress distribution. Therefore, a close understanding of the ground surface properties in relation to heat source movements is necessary to explore the residual stress mechanisms. A typical case study is given in Fig. 4.4, which illustrates the history of the ground surface yield stress (GSYS) in relation to heat source movement. It is found that the GSYS rises shortly after the heat source passes the grinding zone due to surface cooling and martensite transformation.

Figure 4.5 compares the variation of residual stresses with surface hardening. In the case of surface hardening, stresses σ_{xx} and σ_{yy} are both tensile with a maximum of 2.6 times the initial yield stress of the workpiece material.

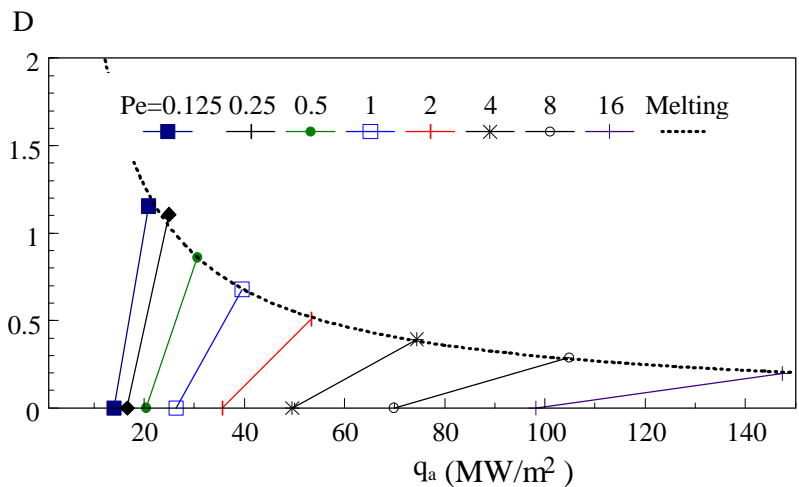


(a) H=0

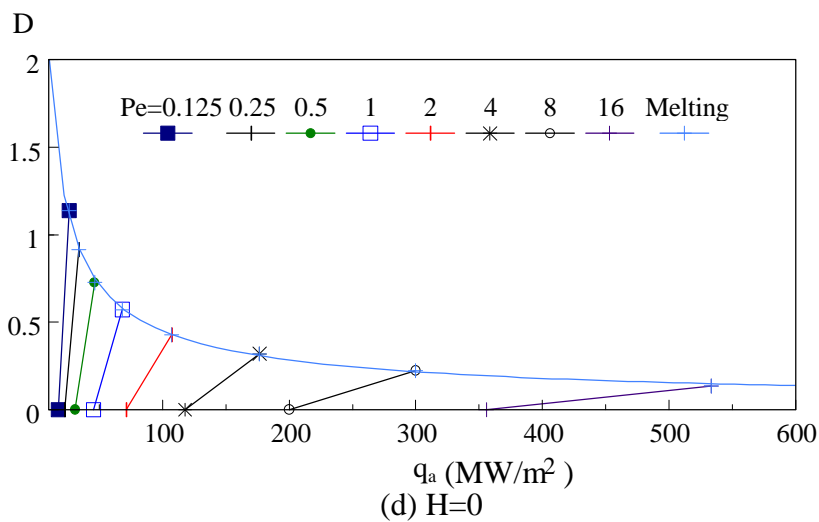


(b) H=1

Figure 4.3 Effect of Pe on martensite depth
($L_c=2\text{mm}$, $l_a=0.25$)



(c) H=0



(d) H=0

Figure 4.3 Effect of Pe on martensite
($L_c=2\text{mm}$, $l_a=0.25$) (continued)

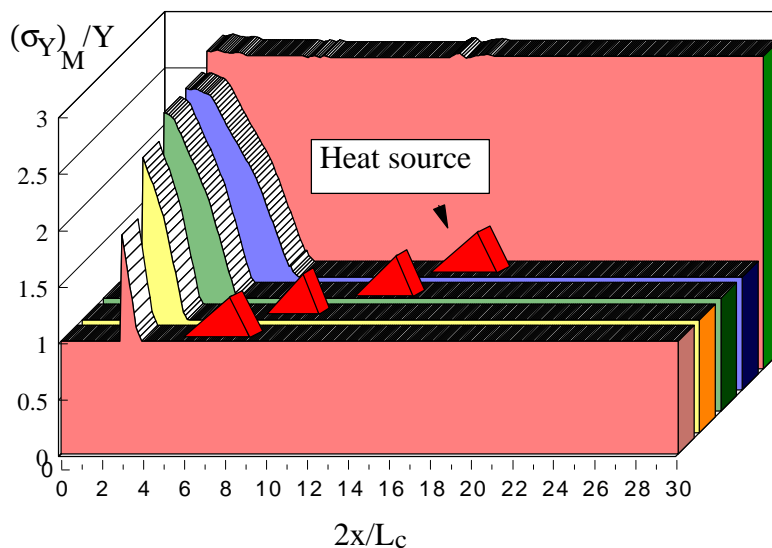


Fig. 4.4 The ground surface yield stresses and heat source movement
($H=0$, $h_a=0.25$, $Pe=1$, $q_a=80\text{MW/m}^2$)

Therefore surface hardening results in higher tensile stresses since the yield stress of martensite is higher. The variation of residual stresses near the surface is nearly linear for both stresses but with rapid change at the onset of phase transformation at a depth of about $D=0.33$. It should be noted that the magnitude of plane stress, σ_{yy} , is always more than that of longitudinal stress, σ_{xx} . In the deeper subsurface, the residual stresses are similar to cases without surface hardening. This indicates that the residual stresses within the martensite zone are directly related to martensite depth. In this sense, therefore, experimental methods currently available may not be sufficiently accurate to predict the actual residual stress distribution when phase transformation occurs.

The volume growth associated with phase transformation also plays an important role in the formation and nature of residual stresses. The permanent volume growth of martensite is restrained by the part without transformation. That is why the martensite volume growth results in compressive residual stresses. The variation of residual stresses with volume growth was investigated for constant material properties and shows somewhat compressive surface residual stresses as shown in Fig. 4.6.

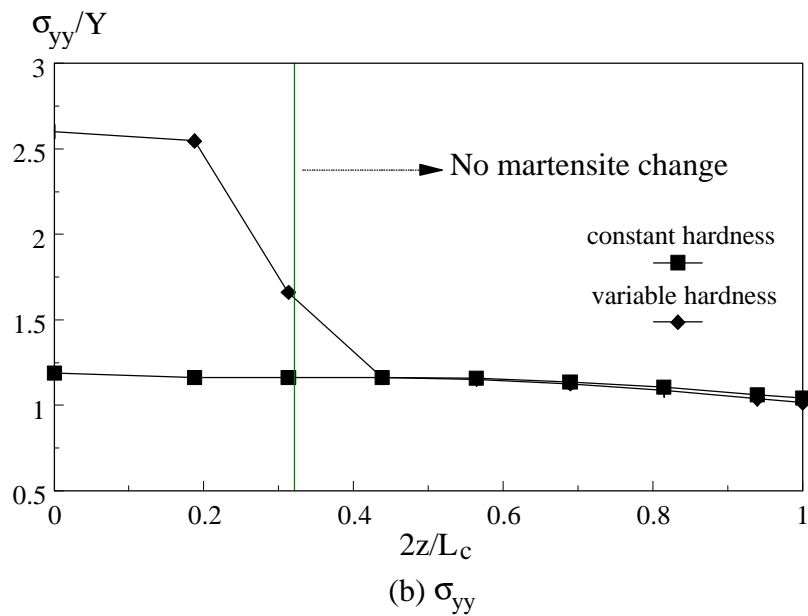
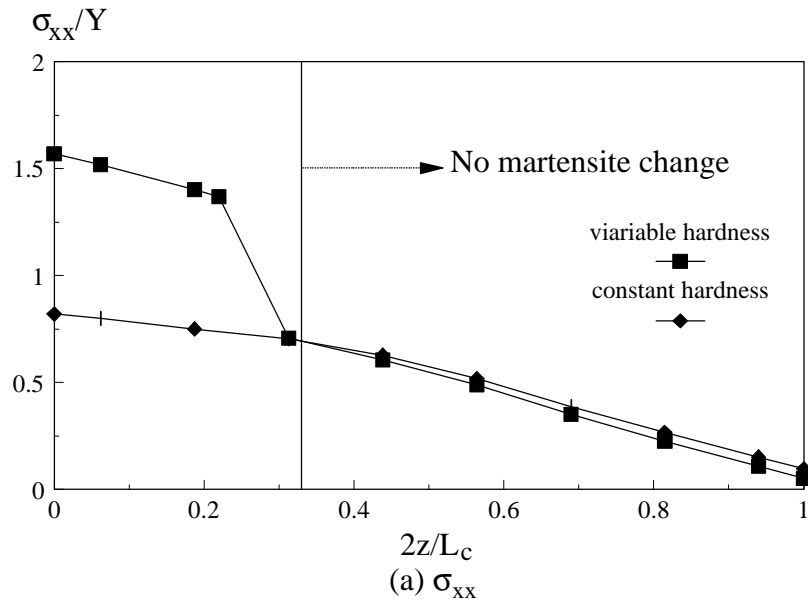
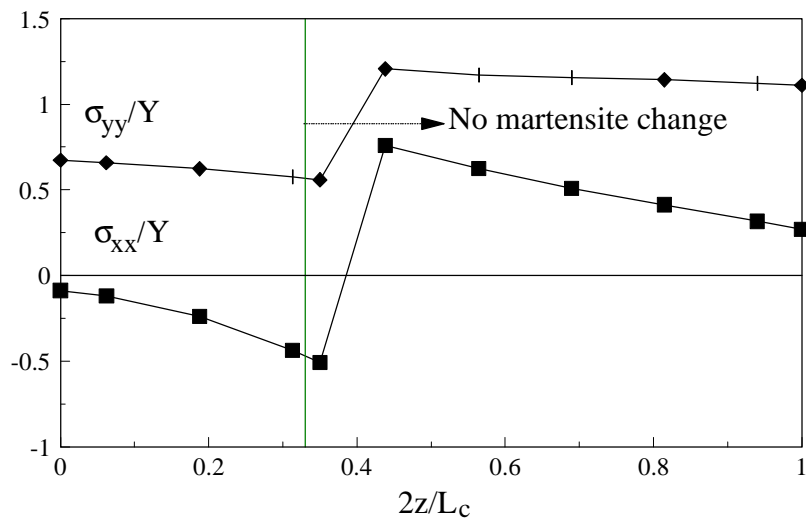
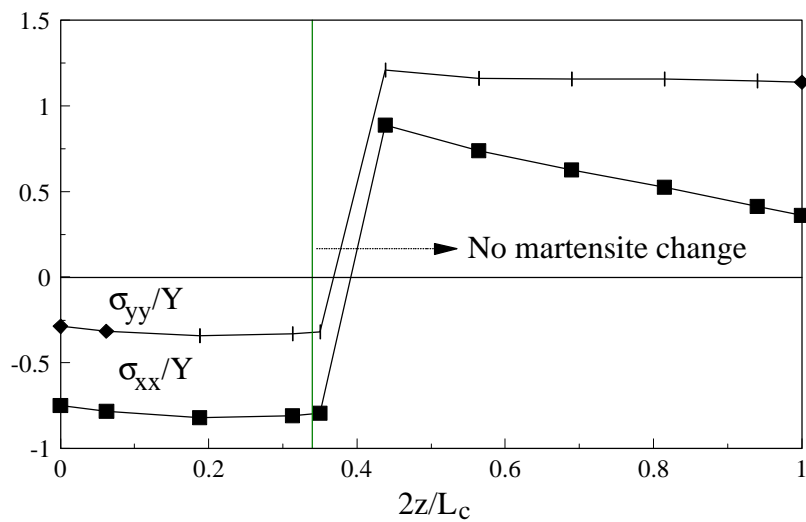


Figure 4.5 Phase change and hardness effect on stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a=0.25$)

The tendency towards more compressive stresses increases as martensite volume increases (Fig. 4.6b). Beyond the martensite layers, a rapid change to tensile residual



(a) 2% volume increase



(b) 4% volume increase

Figure 4.6 Phase change and volume growth effect on residual stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a=0.25$)

stresses occurs due to lack of volume growth. This means that in spite of the surface compressive residual stresses induced by volume growth there is a risk of rapid change of the stress nature from compressive to tensile at the onset of martensite depth.

Surface hardening may be accompanied by volume growth therefore its effect on residual stresses is examined in Fig. 4.7. It shows that surface hardening increases the compressive stresses as surface yield stress is higher than that in the rest of the bulk. Thus surface hardening would result in a higher magnitude of residual stresses regardless of their nature.

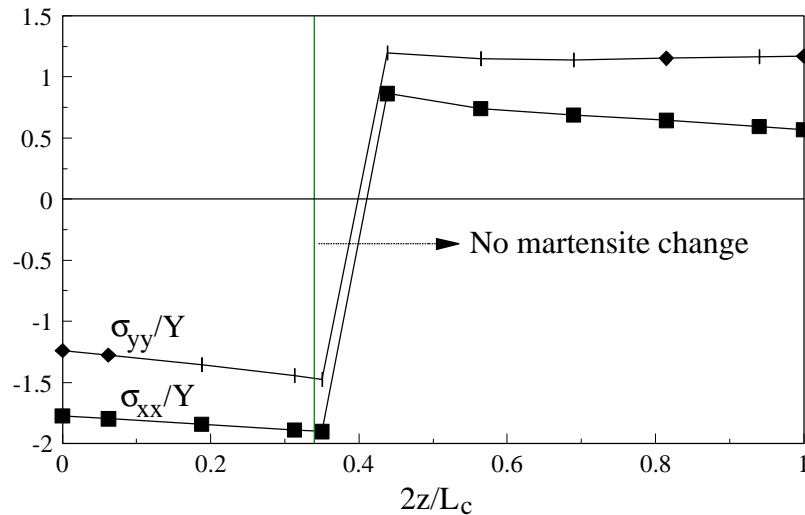


Figure 4.7 Effects of volume growth and hardness increase on residual stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a = 0.25$ volume increase = 4%)

4.3.2 Effect of Grinding Conditions

The role of grinding mechanisms, up- or down-grinding, in residual stress distribution can be investigated by varying l_a as indicated in Fig. 4.8. It shows that, up-grinding (e.g. $l_a = 0.25$) results in a deeper tensile residual stresses in the subsurface. This is attributed to the higher grinding temperature associated with up-grinding which thereby introduces a larger martensite depth when all other conditions are the same. Consequently, an up-grinding process may result in a more critical residual stress distribution. However, Fig. 4.8 shows that

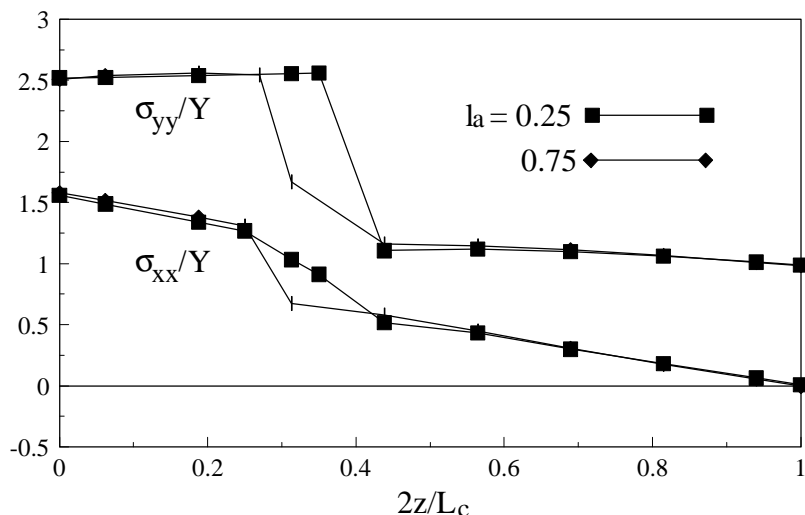


Figure 4.8 Effects of phase change and type of grinding on residual stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a=0.25$ volume increases = 0%)

the surface residual stresses are not affected by the type of grinding processes.

The cooling mechanism relies on convection heat transfer throughout the ground surface and the heat energy diffused into the workpiece material. Cooling has a significant effect on the formation of residual stresses since it lowers the grinding temperature, influences the grinding temperature history and in turn dominates the critical grinding conditions for phase transformation. Figure 4.9 clearly demonstrates the effect of convection heat transfer on residual stress distribution. Under a high cooling rate, a lower grinding temperature is generated and thus leads to a thinner martensite layer. If the grinding temperature is below the austenising temperature, martensite will not form and residual stresses in a workpiece in this case are only those associated with constant material properties. When a martensite layer appears, residual stresses vary linearly with depth. The levels of the maximum residual stresses are not much affected by cooling if the convection heat transfer coefficient is low. For a higher convection heat transfer coefficient, the effect of cooling becomes more dominant as martensite depth is much thinner. The power of the mechanisms of cooling can be enhanced by either increasing the Peclet number or enlarging the convection heat transfer coefficient. It is apparent that both mechanisms result in a different grinding temperature history and thereby cause different cooling rates in the

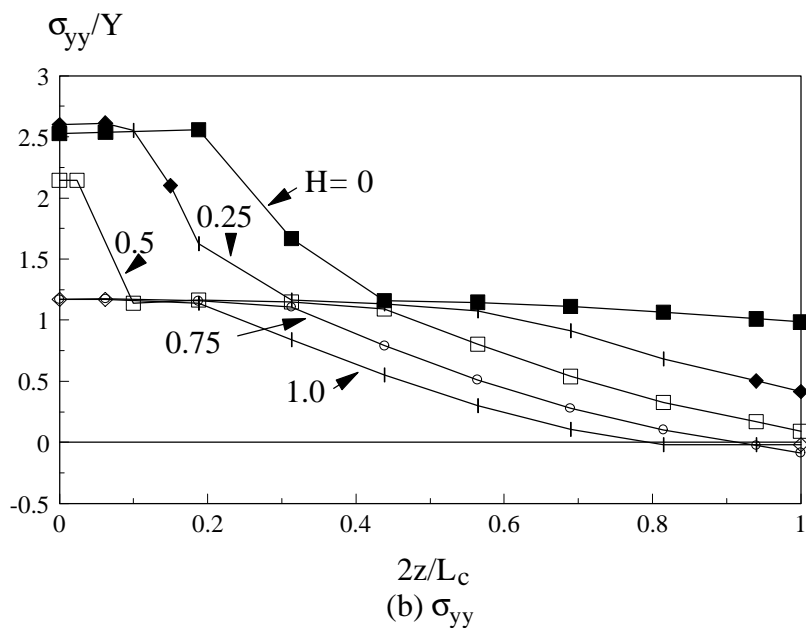
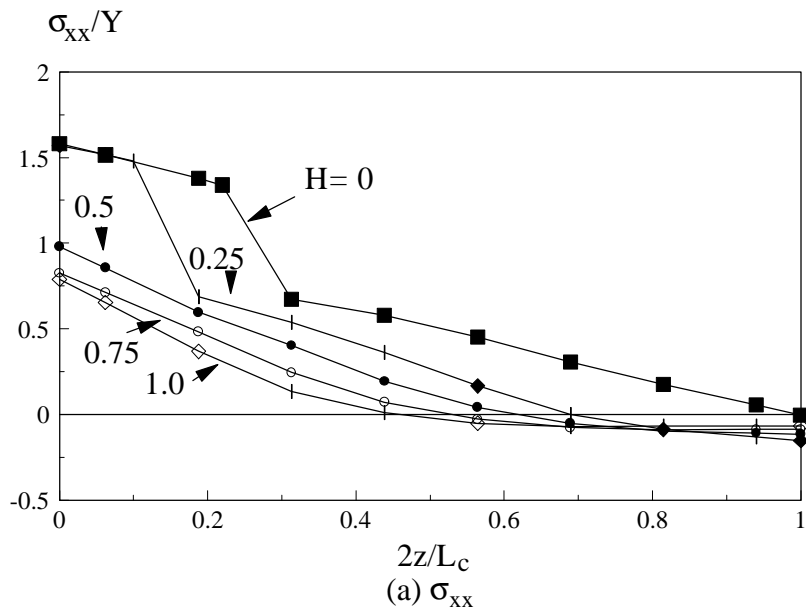
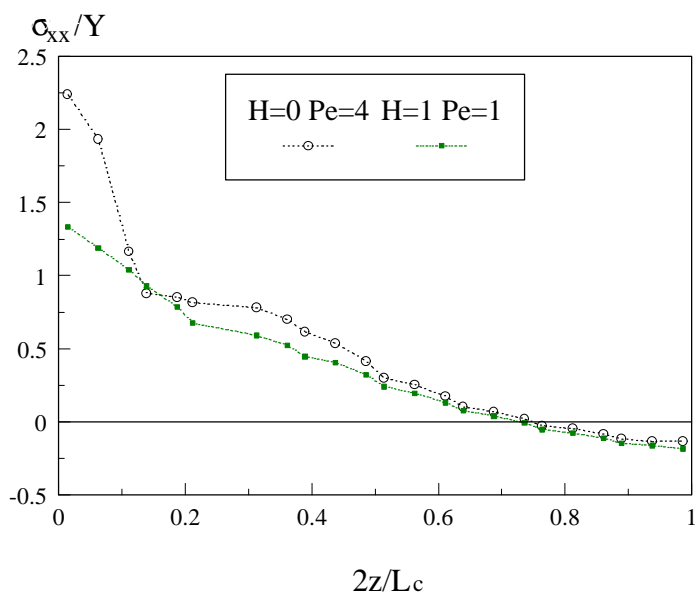
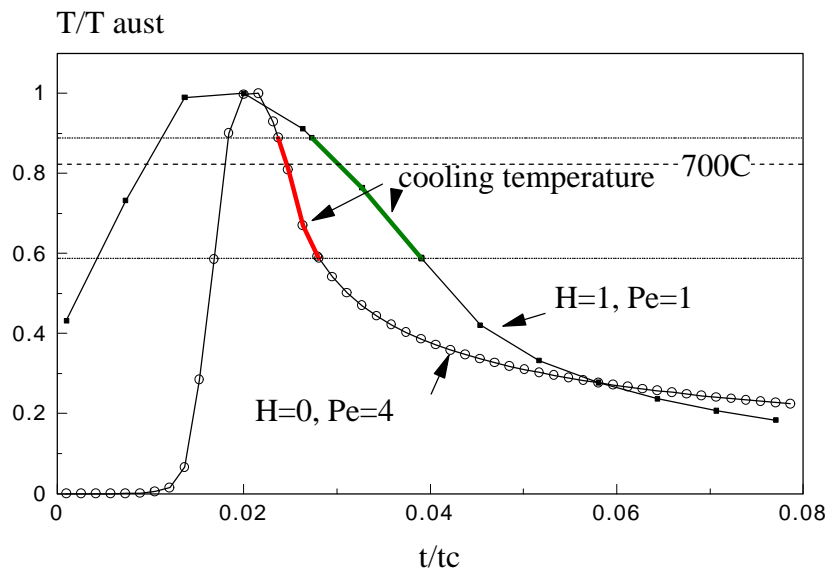


Figure 4.9 Effect of phase change and cooling power on residual stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a = 0.25$, volume increase=0 %)

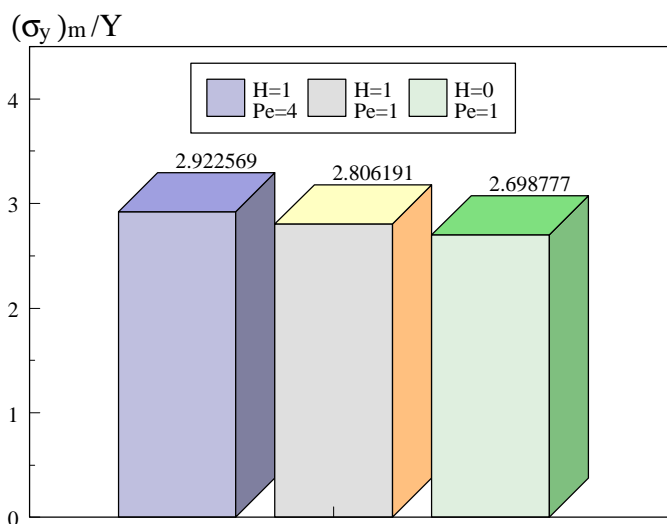
temperature range of interest. The increase of table speed accelerates the cooling rate as less time is required to cool the grinding temperature which in turn elevates the surface hardness as indicated by eq. (2.19). Two cooling rates with their effects on residual stresses are demonstrated in Fig. 4.10.



4.10 Cooling mechanisms and residual stresses ($l_a=0.25$, $Pe=4$, $q_a=110 \text{ MW/m}^2$)

With low table speeds (e.g. $Pe=1$) and uniform cooling (e.g. $H=1$) grinding temperature takes longer to rise. High table speed (e.g. $Pe=4$) with dry grinding conditions ($H=0$), on the other hand, demonstrates a rapid change in grinding temperature which is much higher than that

under a low table speed ($Pe=1$) with uniform cooling ($H=1$). Consequently, the variation of residual stresses would also be sensitive to Pe and H as illustrated in Fig. 4.10b. This confirms that a higher cooling temperature rate yields much greater surface residual stresses. This is attributed to the higher surface hardening associated with a cooling rate at $700\text{ }^{\circ}\text{C}$. The ground surface yield stress associated with different cooling mechanisms and table speeds are clearly illustrated in Fig. 4.11.



4.11 Martensite surface yield stresses and cooling effect

Under a dry grinding condition ($H=0$) with a low table speed (e.g. $Pe=1$) the surface yield stress of martensite, $(\sigma_y)_m$, equals $2.698777Y$. With a high convection heat transfer coefficient (e.g. $H=1$), the surface yield stresses are $2.806191 Y$ when $Pe=1$ and $2.92256 Y$ when $Pe=4$. This explains the effects of grinding conditions on the surface yield stress, on the overall residual stress mechanisms and in turn on the residual stress distribution. Therefore if phase change takes place, close attention should be paid to the mechanism of cooling when residual stresses are concerned.

A further investigation into the influence of heat flux intensity on residual stresses is carried out and the results are shown in Fig. 4.12. In contrast to cooling role, heat generation within the grinding zone raises the grinding temperature thereby increasing the

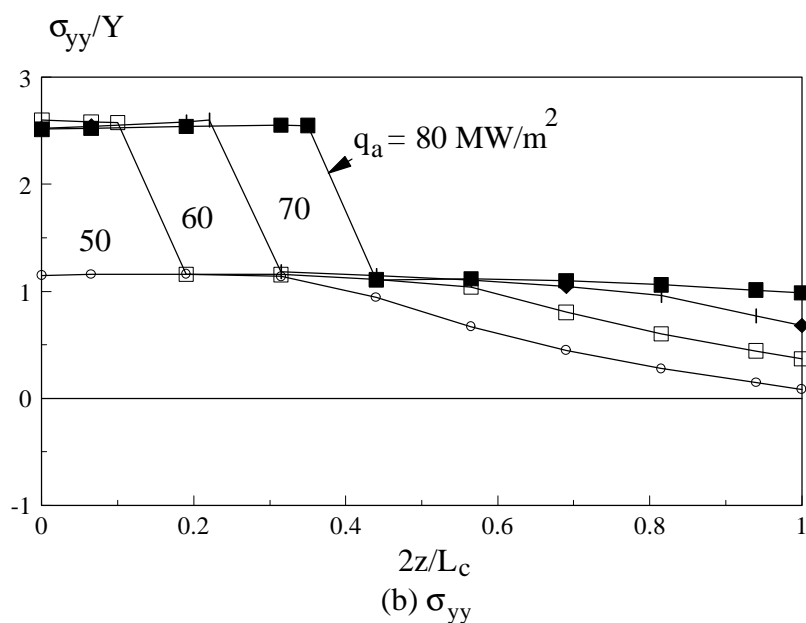
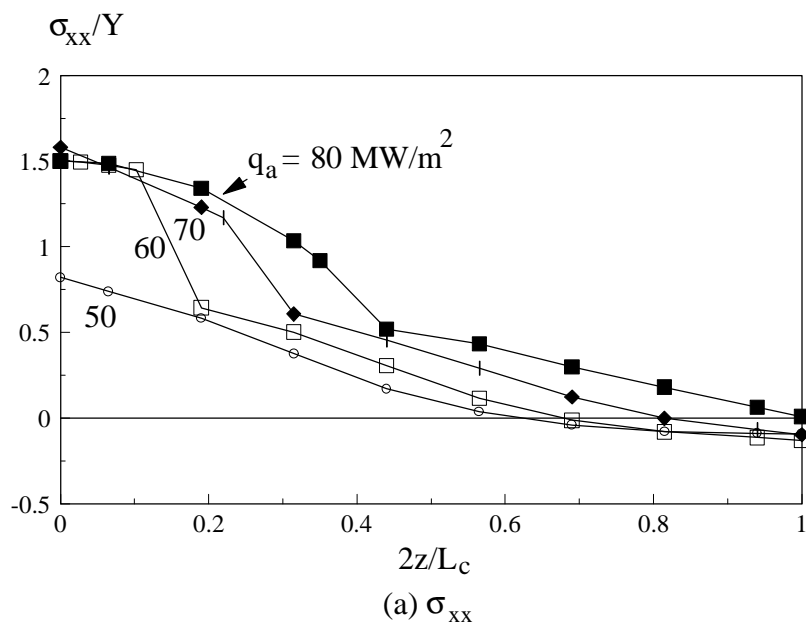


Figure 4.12 Phase change and heat flux intensity effect on residual stresses ($q_a = 80 \text{ MW/m}^2$, $Pe=1$, $H=0$, $l_a=0.25$, 0% volume increase)

tendency of martensite formation. The depth of the hardened layer increases with heat flux intensity as a higher grinding temperature is induced. On the other hand, Fig. 4.12 indicates that a lower heat flux results in a lower grinding temperature and therefore a thinner martensite depth. Thus with a lower heat flux, a smaller tensile residual stresses layer will be generated. As

observed earlier, the layer of residual tensile stresses is directly related to martensite depth and the level of the maximum residual stresses within the martensite layers is not much affected by the strength of the heat flux.

To understand the role of the hardening effects of formed martensite, the effective stress history associated with different heat flux locations is examined in Fig. 4.13. At the early stage of grinding, the workmaterial properties are homogenous and therefore the maximum effective stress is the yield stress, Y . This is shown clearly near the grinding contact zone where a plastic zone is generated due to heating. At a subsequent stage, an additional thin plastic zone appears as the result of cooling. When phase transformation starts, a non-homogenous zone is produced in the vicinity of the ground surface characterized by a varied hardness.

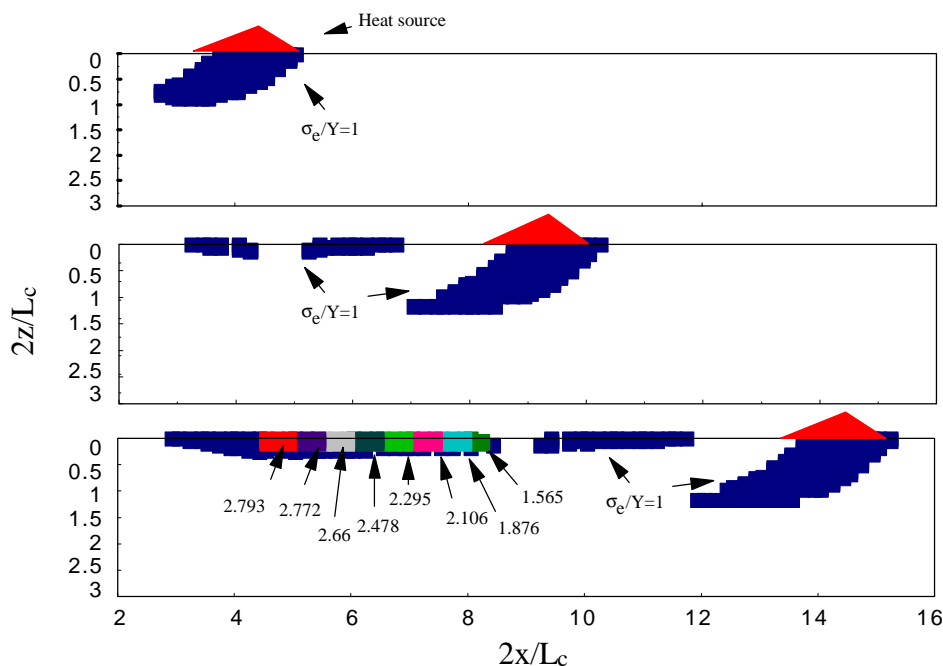


Figure 4.13 Plastic zone development vs Heat source location ($q_a=60 \text{ MW/m}^2$, $Pe=1$, $H=0$, $h=0.25$)

4.4 Summary

This chapter investigated residual stresses due to a set of thermal grinding conditions accompanied by phase transformation and workmaterial property change. Critical grinding conditions to initiate martensite transformation were first addressed. The depth of martensite was then analyzed in relation to grinding conditions. Accordingly, residual stress distributions were studied in relation to the change of surface hardness, the martensite volume growth and the thermal grinding conditions.