RESIDUAL STRESSES CAUSED BY THERMAL AND THERMOCHEMICAL SURFACE TREATMENTS

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ABSTRACT

Thermal treatments discussed in this paper are induction and laser hardening of steel and thermochemical treatments are carburizing, nitriding, nitrocarburizing and boriding of steel.

The principles for the methods are briefly described and experimental data on residual stresses are reviewed. The mechanisms for the residual stress generation is then discussed in some detail supported by computer models. The effect of varying the process parameters on the residual stress is analysed.

KEYWORDS


INTRODUCTION

Thermal and thermochemical heat treatment of metal is usually accompanied by the evolution of large residual stresses. There are a number of reasons for this: (i) thermal stresses due to thermal expansion or contraction of a homogeneous material in a temperature gradient field, (ii) different thermal expansion coefficients of the various phases in a multiphase material, (iii) density changes due to phase transformations in the metal, (iv) growth stresses of reaction products formed on the surface or as precipitates, (v) chemical compositions gradients below the surface.

In the following it will be demonstrated how these factors contribute during thermal and thermochemical surface treatments of steel. The treatments described are carburizing, induction and laser hardening, nitriding, nitrocarburizing and boriding. Several of the processes have been described recently in volume 2 of Advances in Surface Treatments (Ericsson, 1985):

It is appropriate to remind the reader of some definitions. One distinguishes between macro- and micro-residual stresses or with a more elaborated classification residual stresses of the first, second and third kind. The residual stresses treated here are of the macro type equivalent to the first kind. An exception
is in martensitic structures with retained austenite when measurements (but not calculations) refer to stresses in the martensite/ferrite and retained austenite separately i.e. residual stresses of the second kind. In the following stresses will also be discussed that exist during the whole heat treatment process. They are not residual stresses in a strict sense but rather internal stresses. Normally no confusion arises however.

Martensite Transformation Hardening

The principle for the creation of thermal stresses on cooling is shown in Fig. 1 for a simple body (Rose and Hougardy, 1967). The surface temperature decreases more rapidly than the core temperature. This means that the specific volume is greater in the core than in the surface. The volume contraction in the surface is prevented by the higher specific volume in the core. The thermal stress is approximately proportional to the temperature difference and is tensile in the surface and compressive in the core. If the yield stress is never reached the residual stress after finished cooling is zero. If the yield stress, curve b, is lower than the theoretical elastic stress, curve a, the surface material flows in tension and on further cooling becomes too large for the core and compressive surface stresses result with compensating tension in the core. The time of stress reversal is designated $U$. Large thermal stresses are favoured by low thermal conductivity, high heat capacity and high thermal expansion coefficient. Other factors increasing the temperature difference and hence thermal stresses are large thickness dimensions and high cooling intensity of the cooling medium. A large yield stress at elevated temperatures will decrease the degree of plastic flow and thus the residual stress while the yield stress at the ambient temperature puts an upper limit to the residual stress.

In Fig. 2 the added effect of transformation of austenite to martensite in steel is demonstrated. At time $t_1$ the surface temperature falls below the martensite start temperature $M_s$ and the surface starts to transform. It expands and the thermal tensile stresses are counteracted. The stress reversal takes place earlier than otherwise. At the time $t_2$ the core transforms which causes another stress reversal. After cooling transformation induced tensile stresses at the surface dominate over the thermally induced compressive stress.
Residual Stresses

Fig. 2 Formation of residual stress on loading considering thermal expansion and transformation austenite-martensite. (Chatterjee-Fischer, 1973).

As the scope of this treatment is surface hardening the treatment of martensite hardening will be limited to carburizing and induction and laser hardening. The present author has discussed thermal residual stresses from a more general point of view elsewhere (Ericsson, 1982).

Carburizing

Carburized steels present a more complicated picture than steels with homogeneous carbon content. Typical maximum compressive stress values vary between 700 and 300 MPa. Already in the early 1930s it was shown experimentally that large compressive stresses are present in carburized steel by Buhler et al. (1932). This was explained as a result of the larger expansion of the high carbon martensite in the surface relative to the low carbon martensite or non-martensitic transformation products in the core. Typical maximum compressive stress values vary between 700 and 300 MPa.

Koistinen (1958) measured and explained qualitatively the residual stress distribution in carburized steels. He showed that the old explanation was too naive. The basis for his discussion is the fact that the martensite start temperature ($M_s$) decreases with increasing carbon content. The martensite transformation will start where the temperature first cuts the $M_s$ curve, see Fig. 3. The transformation then spreads outwards and inwards. The untransformed austenite in the surface layer is plastically strained in tension due to the core transformation. When the elongated surface is finally transformed large compressive stresses are set up. However, the high retained austenite content close to the surface causes the maximum compressive stress to occur at 50 to 60% of the total case depth, corresponding to about 0.5% C in low carbon steel. The reversal in sign of the residual stress occurs at, or very near the case-core interface. The statement about the position of the compressive stress maximum should not be regarded as a general rule as will be shown in the following.

Computer modelling has been very instructive to explain the mechanism of case hardening more in detail (Hildenwall and Ericsson, 1978, Hildenwall, 1979). In Figs. 4a to 4d one can follow how the transformation of austenite starts below the surface and proceeds and how at the end the austenite in the case is partially transformed to martensite. The evolution of the stress can be seen
in Fig. 5. At first the stress has a typical thermal distribution with tension at the surface and compression in the centre. When a fair amount of the austenite has transformed in the case/core interface the stress there is pushed into compression. When the case transforms into martensite, the stress there becomes compressive and a tensile peak appears below this layer. The tensile peak may for other radii, carbon depths or steel analysis be missing (Burnett, 1977). During the cooling the yield stress is attained at different locations at different times and the plastic deformation taking place affects very much the final stress distribution (Hildenwall, 1979 and Burnett, 1977). The so-called transformation plasticity will also have an important effect (Sjöström, 1982 and 1985, Dennis et al. 1983 and 1985). Transformation plasticity implies that plastic deformation is facilitated by a simultaneous phase transformation.
Usually the residual stress in carburized steel displays a minimum (= maximum compressive stress) a little below the surface, see Fig. 5. Distributions with an intermediate maximum has also been measured, see for instance Coleman and Simpson (1950) and Hildenwall and Ericsson (1980), see Fig. 6.

The reason for the minimum in Fig. 5 is the high retained austenite content in the surface. There is a shift towards the surface of the residual stress minimum for lower surface carbon contents (less retained austenite) (Coleman and Simpson, 1957, and Knuuttila, 1982). The depth of the residual stress minimum is also strongly influenced by the specimen dimension for a constant carbon profile as shown by Coleman and Simpson (1957), Knuuttila (1982) and Ericsson et al. (1983). When comparing specimens of the same size the minimum occurs approximately at the same fraction of the case depth independent of carbon profile (Knuuttila, 1982, and Ericsson et al., 1983). The depth at which the residual stress in the surface layer changes sign increases with increasing diameter of a cylindrical specimen with a certain carbon profile and at the same time the maximum compressive stress increases. The explanation
Fig. 4 Computed phase content at different times after the start of the oil quenching of a cylindrical specimen with 10 mm diameter, 1.0 mm case depth and 0.84% C in the surface. The steel has 0.16% C, 0.7% Cr, 1.0% Ni. (Knuuttila, 1982).
(a) at 8.0 seconds, (b) at 10.1 seconds, (c) at 20.1 seconds, (d) at 1065 seconds.

Fig. 5 Calculated axial stress at 12.2, 16.8, 30.1 and 434.8 seconds after the start of the oil quenching of a cylindrical specimen with 17 mm diameter, 0.9 mm case depth (550 HV) and 0.85% C in the surface. Same steel as in Fig. 4 (Ericsson et al., 1983).

is that a larger diameter means a smaller amount of martensite in the core so the difference between the transformation strain in the case and the average transformation strain in the cylinder is increased.

With increased case depth and constant diameter the maximum compressive stress tends to decrease (Rose and Hougardy, 1967) Ericsson et al., 1983) but the effect is not always significant (Motoyama and Horisawa, 1971). A more severe quenching like water quenching instead of oil quenching, tends to give larger compressive stresses (Coleman and Simpson, 1957), Knuuttila, 1982, and Motoyama
### Residual Stresses

**TABLE 1** Residual Stresses Measured by X-ray Diffraction in Martensite and Austenite in Cylinders with different Diameters made of Swedish Standard Steel SS 2511 (0.16% C, 0.8% Mn, 0.7% Cr, 1.0% Ni, 0.06% Mo) and SS 2523 (0.15% C, 0.9% Mn, 1.0% Cr, 1.1% Ni, 0.1% Mo). Relative Mean Error in Residual Stress < 10% (martensite) Relative Mean Error in Residual Stress < 20% (austenite) (Knuuttila, 1982)

<table>
<thead>
<tr>
<th>Steel</th>
<th>Diam. mm</th>
<th>Case depth 550 HC</th>
<th>Surface carbon cont. %</th>
<th>Depth below surface mm</th>
<th>Residual Stress MPa</th>
<th>Austenite content %</th>
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<tr>
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<td></td>
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<td>austenite</td>
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<td>-170</td>
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<td>0.84</td>
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<td>0.91</td>
<td>0.10</td>
<td>-220</td>
<td>-200</td>
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<td>0.91</td>
<td>0.30</td>
<td>-290</td>
<td>-240</td>
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<td>-220</td>
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<td>0.99</td>
<td>0.88</td>
<td>-240</td>
<td>640</td>
</tr>
</tbody>
</table>

and Horisawa, 1971) which is also supported by calculations (Ericsson et al., 1983).

The measured residual stresses discussed so far are in the martensite/bainite phase. But the structure in the high carbon case contains fairly large percentages of retained austenite. In an extensive work by Beumelburg (1974) the residual stress and the retained austenite content were measured in 4 different steels carburized to between 0.45 and 1.20% C in the surface. Most of the steels were annealed at 170°C. As a general trend the austenite stress decreased with increased retained austenite content (9-65%) and was tensile except for more than 40% austenite. The martensite stress increased and was compressive below 10% and most often slightly tensile above 10% retained austenite. In another fairly extensive study by Knuuttila (1982) with austenite contents between 15 and 32% the stress was compressive in both phases except in one
Fig. 6 Residual stresses versus depth below the surface in a 10 x 50 x 80 specimen, 0.65 mm case depth (550 HV) and 0.82% C in the surface. The steel has 0.18% C, 0.7% Cr, 3.0% Ni and 0.05% No. (Hildenwall and Ericsson, 1980).

single specimen with tensile stress in the austenite, see Table 1. The magnitude in the austenite was as a rule slightly smaller than in the martensite, except in the odd specimen where the magnitude in the austenite was much larger. Obviously more studies are needed to clarify the relation between the residual stress in martensite and retained austenite. The computer modelling so far has not treated the phases separately.

Sub-zero treatment of as-carburized steels reduces the retained austenite content due to martensite formation. It is intuitively to be expected that the martensite stress should become more compressive due to the swelling of the case. Beumelburg (1974) found a subsequent shift of the residual stress in the martensite in the compressive direction and of the residual stress in austenite in the tensile direction. A few studies however have shown a more complicated pattern, the compressive stress in the martensite layer just below the surface is reduced about 50 MPa but deeper into the material it is increased about 50 MPa, see Fig. 7 (Magnusson, 1980).

A low temperature temper (170°C) is reported to shift the residual stress in the tensile direction in the martensite. A tensile shift has also been observed in the retained austenite by Coleman and Simpson (1957) and Beumelburg (1974).

Very often in gascarburizing a thin soft layer (10 μm) is formed on the surface due to oxidation of alloying elements like Cr and Mn. the hardenability of the dealloyed layer is relatively low and therefore a fine perlite is formed early during the cooling. This layer becomes strained in tension during the martensite formation of the case and tensile stresses arise. The mechanism is discussed in detail by Hildenwall and Ericsson (1980).

Induction Hardening

In induction hardening of steel one has to consider both the heating and the cooling stage. The heating is caused by eddy currents generated with an induction coil. The depth of the eddy current layer (skin depth) δ is mainly determined by the frequency f of the current in the coil, δ=1/√(2πf).

One usually distinguishes between stationary and progressive induction hardening. In the former the coil covers the whole area to be heated and in the latter the workpiece is moved through the coil which consists of one or very few turns. In both cases the cooling is usually done by spraying water on the workpiece. Very often the hardened zone is tempered at low temperature (170°C)
Residual Stresses

Fig. 7 Measured distributions of retained austenite and residual stress versus depth below the surface in a cylindrical specimen with 15 mm diameter, 0.80 mm case depth (550 HV) and 0.85% C in the surface. The same steel as in Fig. 4 (Magnusson, 1980).

afterwards. The residual stresses in the case are compressive and usually of the order of 500-1000 MPa.

By computer modelling Melander (1983), (1985a) and (1985b) has explained the mechanism of stress generation. In Figs. 8a to 8h calculated diagrams are shown for a 40 mm diameter cylinder of the steel AISI 4142 heated with 300 kHz for 33 seconds and after 4.5 seconds water sprayed for 80 seconds. The temperature at various depth is shown in Fig. 8a. The turn off of the heating and the start of the water spraying is evident in the surface temperature curve. The maximum temperature is reached the later the deeper the location into the specimen. The heating rate below the Curie temperature (770°C) is more rapid than above as to be expected. The reason for a more rapid temperature rise just before the plateau is an increase in the coil current. In the temperature range above Ac3 (800°C) where the austenite formation takes place the temperature stays almost constant for a while due to the absorption of heat of transformation. This is clear from Fig. 8c which shows the austenite content versus time for various depths. The thickness of the austenite layer is of course determining the hardening depth. The thickness can be seen in Fig. 8d and is at a maximum of about 4 mm after 33 seconds. The martensite layer formed is shown in Fig. 8e. The development of the axial stress is illustrated in Fig. 8g versus depth at various times and in Fig. 8h versus time for various depths. The final residual stress distribution (axial, tangential and radial) is shown in Fig. 8f. Study Fig. 8g, 8d and 8b together. After 10 seconds the stress is compressive in the surface layer due to thermal expansion of the original structure. After 23 seconds the stress is shifted.
in the tensile direction due to the formation of more austenite which has a lower specific volume. After 40 seconds the austenite in the outer layer of 2 mm is shifted in the compressive direction due to martensite formation. This finally causes compressive axial and tangential stress down to a depth of about 5 mm which is a little below the case/core interface. No tensile peak is formed in this example below the compressive layer which is sometimes reported. It should be pointed out that these computer calculations in many cases give quite good agreement with measured temperatures, hardnesses and residual stresses (Melander, 1983 and 1985a). In Fig. 9 is shown a comparison of calculated and measured residual stresses. One feature that is very often observed experimentally but has not been predicted by calculations is a shift in the tensile direction of the residual stress closest to the surface. It is not due to decarburization.

At the edges of the induction hardened zone tensile stresses can occur, see Fig. 10 (Ishii et al., 1971). They are probably caused by a plastic deformation in compression during heating (to maximum temperature below Ai), followed by an elastic deformation in tension during the cooling to the final temperature.

At progressive induction hardening of a sufficiently long cylinder a steady state condition may develop in that a certain temperature distribution is
Melander (1985a, 1985b) has carried out such a computer modelling. Figure 11a shows measured and calculated temperature profiles for a 40 mm diameter specimen of AISI 4142 steel heated by 40 kHz induction voltage and moved with a speed of 3.47 mm/sec through a single coil and cooled by a water spray. The measured and calculated hardness is shown in Fig. 11b and the residual stress distribution is shown in Fig. 11c. The measured residual stress displays a typical minimum just below the surface which is however not reproduced by the calculations. The magnitude of residual stress is fairly normal.

If the cooling time seen by a travelling point on the cylinder is too short heating of the surface may occur by heat conduction from the warm core, see Fig. 12. This effect may be used for low temperature tempering of the induction hardened layer. Such a temper will reduce the residual stresses.
Fig. 8 Calculated values for induction hardened (300 kHz) cylinder with 40 mm diameter made of steel AISI 4142. (a) Temperature versus time for different depths, (b) Temperature versus depth at different times, (c) Austenite content versus time for different depths, (d) Austenite content versus depth at different times, (e) The final martensite and hardness distributions, (f) Residual stresses versus depth, (g) Axial stress versus depth at different times, (h) Axial stress versus time for different depths, (Melander, 1985a and 1985b)
Residual Stresses

Fig. 9 Calculated and measured axial residual stresses in an induction hardened cylindrical specimen with 40 mm diameter and 4.7 mm case depth (550 HV) made of steel AISI 4142. (Melander, 1985a and 1985b).

Fig. 10 Residual stresses and hardness of static induction hardened surface. Diameter of specimen is 190 mm, frequency 10 kHz and heating time 50 seconds. (Ishii et al., 1971).
Fig. 11 Calculated and measured results for a progressively induction hardened specimen with 40 mm diameter, 1.5 mm case depth (550 HV) made of steel AISI 4142. (Melander, 1985a and 1985b)

Laser Hardening

Laser hardening has many similarities with induction hardening. The surface layer of the steel is rapidly heated into the austenitic temperature range and then quenched. So in both cases there is a rapid heating and a very short holding time at the peak temperature. There are differences however. In
Residual Stresses

Fig. 12 Calculated results for different length of the cooling zone for progressive induction hardening of a 10 mm diameter specimen. (a) Workpiece with different cooling zones, (b) temperature versus time 1 mm below the surface. (Melander, 1985a and 1985b).

Laser hardening the heat is generated at the surface by the laser light while in induction hardening the heat is generated down to certain depth. The quenching after laser heating is normally achieved by heat conduction into the core while after induction heating water quenching is the rule. The laser heating is normally carried out along 1-10 mm wide straight or curved traces on the surface. Therefore there are also geometric similarities between welding and laser hardening.

Several computer models have been developed for the calculation of the temperature distribution under a laser beam (Godfrey et al., 1981, Kawasumi, 1981, Courtney and Steen, 1981, Ashby et al., 1985, and Li, 1984). An example is shown in Fig. 13 for the power density of 940 J cm\(^{-2}\) and experimental curves are shown in Fig. 14 for the power density of 2300 J cm\(^{-2}\). The rise time of the temperature is obviously shorter than for induction heating, Fig. 8a. Notice also that the temperature in the core is always lower than at the surface in the laser hardening case while the surface and interior temperature may cross each other in the induction hardening case.

There is little time for carbide dissolution and a coarse carbide (pearlite islands) can give rise to martensite islands in a ferritic matrix. (Li, 1984, Chatterjee-Fischer et al., 1984). High retained austenite contents have been reported in the outer layers of laser hardened medium carbon steels (Chatterjee-Fischer et al., 1984, Melander, 1985a, Ericsson, 1985), while the same steels exhibit no retained austenite after induction hardening.

There is little data available about residual stresses around a laser hardened track. In Table 2 values from measurements across a single 8 mm wide pass on a 0.4% carbon steel is shown and in Fig. 15, a depth distribution for the same type of steel. The distribution is similar to the distribution after induction hardening and, one can add, after carburizing. Common features with carburizing is the martensite transformation start below the surface and the high retained austenite content.
Fig. 13 Calculated thermal cycles of a laser-hardening run for an energy input of 940 J/cm². (Li, 1984).

Fig. 14 Measured temperatures at different depths below the surface. Curve 3 at 0.86 mm below the surface and curve 2 at 4.70 mm. (Yao and Melander, 1983)

A special case of laser hardening using a toric mirror to heat the whole circumference of a cylindric specimen has been treated recently. (Melander, 1985a, Melander and Yao, 1985). Figure 17a to f shows calculated temperatures, austenite contents and axial stresses as functions of time and depth respectively for a 57 mm diameter cylinder in the steel SAE 4142. The travel speed through the toric mirror was 0.152 m/min, the laser beam width 8.175 mm and the input power 6.60 W/m². The temperature in the surface rises quickly to 950°C and then decreases to the same temperature as the centre (about 300°C). Due to
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Fig. 15 Residual stress distribution resulting from laser transformation hardening. (Li, 1984, Gnanamuthu and Shaw, 1979).

Fig. 16 Residual stress distribution around a weldment in steel SAE 1045. (Yu, 1977).
the limited mass of the cylinder the temperature does not decrease further. (In actual tests the cylinder had to be water cooled at the end). The austenite forms to a depth of about 0.8 mm, Fig. 17d. During the heating compressive stresses develop in the surface due to thermal expansion, Fig. 17c, which quickly change into tensile stresses when the austenite forms. The core develops tensile stresses. When the martensite starts to form compressive stresses appear in the surface. The depth distribution at the end, Fig. 17f, displays compressive stress in the martensite region and a tensile peak below. If the cooling had been continued down to room temperature, a completely martensitic
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Fig. 17 Calculated values for a cylinder of steel SAE 4142 with 28.6 mm diameter laser hardened by help of a toric mirror. (a) temperature versus time, (b) austenite content versus time, (c) axial stress component versus time, (d) austenite distribution after 24 seconds (e) martensite distribution after 100 seconds (end of calculation), axial (\( \sigma_x \)), tangential (\( \sigma_y \)) and radial (\( \sigma_z \)) stress versus depth after 100 seconds. (Melander, 1985a, Melander and Yao, 1985).

case should have been obtained with much larger compressive stresses. Notice that the stress minimum is below the surface in Fig. 17f like in the experimental curve, Fig. 15. Measurements on 15 mm diameter cylinders of SAE 4142 steel.
hardened in this way show compressive stresses of between 340 and 450 MPa at
the surface and between 480 and 660 in the minimum and that retained austenite
contents vary between 3 and 7% in the surface region. (Ericsson et al., 1985,
Melander and Yao, 1985).

Nitriding

Residual stress generation due to nitriding of steel has not been studied so
much as through hardening or carburizing. An overview paper has recently been
published in German (Koch, 1982) and some theoretical discussions are found in
(Mittenmeijer, 1981, 1983, Rozendaal, 1984, Oettel and Ehrentraut,
1985).

Nitriding is carried out in the ferritic temperature range, usually between
500 and 550°C, in partially dissociated ammonia for up to 120 hours. the
nitrogen activity in the gas is usually so high that a layer of γ'-nitride
(Fe₄N) and even ε-nitride (Fe₂₋₃N) is formed. During recent years so-called
plasma-nitriding has gained wider use. The nitrogen uptake is then activated
by glow discharge. The process time can be shortened or the process can be
carried out at a lower temperature.

In nitriding the main cause for residual stress in the metal phase is the
chemical gradient of nitrogen from the surface inwards. In carbon steels the
nitrogen is in solid solution at the process temperature and iron nitrides are
precipitated during the cooling. The resulting residual stresses are small.
If the steel is alloyed with elements with higher affinity for nitrogen, alloyed
nitrides are precipitated already during the nitriding. This is especially
pronounced with alloying elements of very high affinity for nitrogen like Al,
V or Ti. The residual stresses then become greater. If the steel is quenched
after the nitriding thermal residual stresses are superimposed and larger
compressive stresses are obtained. Examples of residual stresses in different
steels are shown in Fig. 18. Plasmanitriding gives similar residual stress
values as gasnitriding. (Koch, 1982). The residual stress in the nitride
layer on the surface has been the subject of two recent papers (Rozendaal,
1984, Oettel and Ehrentraut, 1985). The residual stress in the γ'-nitride is
highly compressive while in the ε-nitride it can become tensile at the outer
surface, see Fig. 19.

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TABLE 2 Distribution of Residual Stresses on the Surface across a Laser
Hardened Track on Steel SAE 1045. Chatterjee-Fischer et al., 1984)

<table>
<thead>
<tr>
<th>Distance from centre line mm</th>
<th>Residual stress MPa</th>
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<tr>
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<tr>
<td>1</td>
<td>-25 ± 54</td>
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<tr>
<td>2</td>
<td>-225 ± 30</td>
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<tr>
<td>8</td>
<td>-354 ± 21</td>
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No comprehensive quantitative model has yet been developed for nitriding, but the basic principles are well understood (Rozendaal et al., 1984, Oettel and Ehrentraut, 1985). Contributing factors in the diffusion zone in the metal phase are the composition gradient of nitrogen, the precipitation of nitrides which have a larger atomic volume of metal than the matrix and thermal stresses and in the compound layer misfit between \(\gamma'\)- and \(\varepsilon\)-nitride in two phase layers, precipitation of \(\gamma'\)-nitride in original \(\varepsilon\)-nitride and formation of nitrogen.
Fig. 18 Residual stress in gasnitrided in slowly cooled specimens. (a) normalized carbon steel SAE 1015, (b) QZT DIN 37Cr4, (c) normalized 27CrAl6. (Koch, 1982).

Fig. 19 Residual stresses in the compound layer on the steel DIN 30CrMoV9 as a function of the depth under the surface. (Oettel and Ehrentraut, 1985).

filled pores. Finally a very significant cause is the interaction between the compound layer and the metal matrix due to different atomic volumes of the metal and different thermal expansion coefficients. The former factor is
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usually expressed by help of the Pilling-Bedworth (PB) ratio which for pure iron nitrides are 1.16 ($\gamma' / a$) and 1.15 ($\epsilon / a$) (Rozendaal et al., 1984). The interaction should give a tensile stress contribution to the metal surface zone and a strong compressive stress contribution to the compound layer.

One has tried to evaluate numerically some of the factors. The compositional gradient stress can be set proportional to the difference between the local and the average concentration of nitrogen in the steel (Mittenmeijer, 1983). Figure 20 shows how the calculated surface macrostress in the metal varies with time and development of the nitrogen concentration profile. Notice that the surface stress is compressive and increases with increasing surface nitrogen content in the beginning. Stress relaxation due to dislocation movements in the metal can also occur. (Rozendaal et al., 1984).

![Diagram](image)

Fig. 20 (a) Development of the nitrogen concentration profile on nitriding $\alpha$-iron specimens of thickness 2 mm in a gas atmosphere of 13% NH$_3$ and 87% H$_2$ at 560°C. (b) Surface macrostress ($\sigma$), nitrogen surface concentration ($C_s$) and average nitrogen concentration ($\bar{C}$) of the same specimen as in (a) as a function of time. (Mittenmeijer, 1983).

The various contributions to the residual stress in the compound layer has been depicted in Fig. 21. The contribution (a) is due to the PB effect, (b) is due to precipitation of $\gamma'$-nitride in $\epsilon$-nitride on cooling and (c) due to the larger thermal contraction of $\epsilon$-nitride relative to $\gamma'$-nitride. The total
residual stress in the compound layer can be slightly tensile at the outer surface and strongly compressive nearer the nitride metal interface.

There are a number of ferritic treatments similar to nitriding but also involving carbon, so called nitrocarburizing. Examples are nitemper, carried out in gas, and tufftriding, carried out in a salt bath. The treatment times are much shorter than for nitriding 1-4 hours instead of 12-120 hours, and the temperature higher, typically 570°C instead of 500-550°C. In nitrocarburizing e-carbonitride is formed on the surface and the diffusion zone is usually not so deep as for nitriding due to the short process time. The mechanism of residual stress formation is the same as for nitriding.

**Boriding**

Boriding of steel is carried out in powder, salt bath or gas at 800-1000°C. Boron reacts with the steel to form Fe₂B and FeB. By choosing suitable conditions a monophase layer of Fe₂B can be formed. The interface between the steel and the boride layer is very irregular, sometimes described as tooth shaped. In two references specific attention has been paid to residual stresses (Permyakov et al., 1969 and Liliental and Tacikowski, 1980). The residual stress in the boride layer at room temperature is mainly compressive, as measured by mechanical methods, Fig. 22 and 23. The explanation given to the occurrence of compressive stress is the difference in thermal expansion coefficient between the boride phases and the steel. The thermal expansion of the metal is larger than that
Residual Stresses

![Residual Stresses graph](image)

**Fig. 22** Residual stresses in boride layers on pure iron after 2 h boriding by electrolysis in molten borax. Different temperatures were used: curve 1 850°C, curve 2 950°C and curve 3 1050°C. (Permyakov 1969).

**Fig. 23** Residual stress distribution in the compound layer on pack borided SAE 1045 steel. The post heat treatments after cooling were (a) none, (b) normalized, (c) normalized, hardened and tempered at 450°C, (e) normalized, hardened and tempered at 200°C. (Liliental and Tacikowski, 1980).

of the boride and hence the boride layer will stand under compression after cooling from the reaction temperature. As a consequence the compressive residual stress should be the larger the higher the reaction temperature which is also observed, Fig. 22. It has been pointed out that the density of the steel after cooling from the boriding temperature should also affect the residual stress. The density increases in the order martensite, tempered martensite and pearlite/ferrite. Figure 23 shows that the larger the density the the compressive stress. A martensitic steel structure actually causes tensile stresses in the boride layer, Fig. 23e.

**SUMMARY**

Large compressive stresses in the surface region is normally obtained by carburizing, induction and laser hardening, nitriding and boriding of steels.
Contributing factors for carburizing, induction and laser hardening are thermal stresses and density changes due to martensite formation. In carburizing the carbon gradient affects the residual stress formation indirectly by affecting the Ms temperature. For nitriding contributing factors are different thermal expansion coefficients for the phases present, growth and precipitation stresses for nitrides and stresses due to the nitrogen composition gradient. Thermal stresses can also be involved. For boriding the stresses due to the composition gradient is probably not so important as for nitriding. Martensite transformation stresses can arise in the steel substrate below the boride layer if the steel is quenched after the boriding treatment.

REFERENCES


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