Experiments with 'medieval steel' plates

Alan Williams

Abstract

Some experiments on quenching and tempering were carried out on a sample of modern ultra-pure steel and two specimens of 16th century armour, to observe changes in hardness with time at low tempering temperatures. The hardness of the specimens of armour fell more rapidly than might have been expected by comparison with modern steels. This has suggested a reason why gilding was found to be a difficult process to combine with hardening by armourers.

A recent paper has described attempts to reconstruct the processes involved in the decorative gilding of armour. It is asserted, inter alia, that ‘the microstructure and properties of martensitic steel which was tempered at 450-500°C ... were not significantly altered by a further heating at 300-380°C for gilding and blueing’ (Anheuser 1997, 38).

Unfortunately, in the experience of the author, this statement is an oversimplification of the problems which 16th century armourers had to overcome — perhaps because it is based upon the reported behaviour (Grange *et al* 1977 and 1956) of modern alloys extrapolated to 16th century steels. Grange and his co-workers used pure iron-carbon alloys, to which controlled amounts of manganese and other elements were then added for their 1977 paper; but for their 1956 paper low-carbon steels were used which also contained manganese in amounts varying from 0.57% to 1.85%. The time-temperature parameters which Anheuser (1997) uses originated in the 1956 paper.

Heat treatment experiments

It may be helpful to recount some experiments that the author has carried out on the heat-treatment of medieval steel from armour plates. Two specimens from 16th century armours were tested together with a modern (‘pseudo-medieval’) steel of similar carbon and manganese content.

This work was done as background for a recent monograph on Greenwich armour (Williams and de Reuck 1995). Armour of the highest quality produced at the English Royal Workshops at Greenwich in the second half of the 16th century was made of bloomery steel that was not only heat-treated to improve its performance but also decorated by fire-gilding and blueing.

Specimen A was a vambrace (upper arm defence) plate made in North Italy, *c*1570. As received, this was a pearlitic-ferritic steel of average hardness 183 VPH. It was cut into pieces approximately 50x50x0.9mm for these experiments.

Specimen B was a fragment from a pauldron (shoulder defence) made in South Germany, probably in Innsbruck, *c*1550. By modern standards this is a low-alloy steel and is chemically fairly similar to specimen A, but did seem to be more homogeneous on microscopic examination. As received, it had a microstructure of tempered martensite with little visible ferrite, and average hardness 514 VPH. This was also cut up into pieces, of approximate dimensions 50x50x1.7mm.

Samples from these two steels, whose compositions are given in Table 1, were put through the sequence of heatings that was probably needed for the hardening and decoration of armour. Electric kilns were used for the heating. Hardness measurements were carried out with a GKN microhardness tester (100gf load) at 10 points on the surface of embedded and polished samples.

A sample of steel from A was water-quenched, tempered for 15 minutes at 450°C, and then ‘gilded’, *ie* heated for 5 minutes at 350°C, and ‘blued’, *ie* heated for 10 minutes at 300°C. Its final hardness was 283 VPH.

A sample of steel from B was water-quenched and tempered in the same way and then also ‘gilded’ and ‘blued’. Its final hardness was 339 VPH, which accords reasonably well with observed results for South German armour. Another sample of B was treated similarly but tempered for 30 minutes, *ie* it was ‘overtempered’. Its final hardness was 229 VPH.

Tempering both these specimens of armour at gilding/blueing temperatures for relatively short times seemed to soften them markedly. Further experiments were carried

Table 1: Composition of steel samples (wt%)

Sample	A	B	C
C	0.50	0.49	0.50
Si	0.24	0.02	0.58
Mn	0.02	0.07	0.02
Ni	*	0.03	nd
P	*	0.049	-
S	*	0.007	-
Al	-	0.007	-

Key:
nd = not detected, * = negligible, - = not determined

Data for samples A and C are from bulk EDAX analyses, except for carbon which was estimated metallographically. Data for sample B are from spectrographic analysis.

out to try and clarify this, varying time and temperature and making hardness readings at intervals.

A sample of A which was austenitized for 30 minutes at 850°C and then water-quenched had a hardness of 738 VPH. When this sample was subsequently tempered at 350°C for 30 minutes the hardness was found to be 494 VPH. After 1 hour this fell to 455 VPH. If this was then 'blued', *ie* heated for a further 15 minutes, the hardness fell still further to 385 VPH.

A sample of B was austenitized in the same way and water-quenched; its hardness rose to 678 VPH. On austenitizing and then water-quenching a sample of B and tempering at 350°C for 30 minutes the hardness was 440 VPH. After 1 hour this fell to 426 VPH. If this was then 'blued', *ie* heated for a further 15 minutes, the hardness fell still further to 364 VPH. These results are shown in Figure 1. The fall in hardness seemed to be more rapid than expected, and so it was decided to compare samples A and B with a modern steel of equally low manganese content (sample C). This was a low-carbon, manganese-free steel supplied to the Royal Armouries for their restorations by RARDE (now DERA) some years ago. On being heat-treated it did not behave in quite the same way as a modern steel might have been expected to do, but in a manner similar to the 16th century specimens (indeed its manganese content was lower than theirs). It was also cut up into samples of approximately 50x50x2.4mm.

After austenitizing for 30 minutes at 850°C and then quenching into water, its hardness was found to be 698 VPH. If this specimen was then tempered for 60 minutes at 600°C its hardness fell to 208 VPH. This was effectively the same hardness as when received (202 VPH). On being water-quenched and then reheated for 60 minutes at 450°C, the hardness of another sample fell to 247 VPH. On being water-quenched and then reheated for 60 minutes at 350°C the hardness of another sample fell to 285 VPH. These results are shown in Figure 1 together with those for samples A and B.

It was decided to perform some more experiments with steel C, tempering at a constant temperature. On being water-quenched and then reheated for different times at 300°C the hardness after 20 minutes was 414 VPH (rather lower than expected), after 40 minutes it was 455 VPH, and after 60 minutes it was 333 VPH. The last two of these observations were repeated by taking another specimen of the same steel; after being water-quenched and reheated for 40 minutes at 300°C it had a hardness of 409 VPH, which after 60 minutes fell to 312 VPH. Figure 2 was plotted using the average of these hardness results.

Both samples A and B showed a faster rate of softening than would be expected from modern steels, presumably

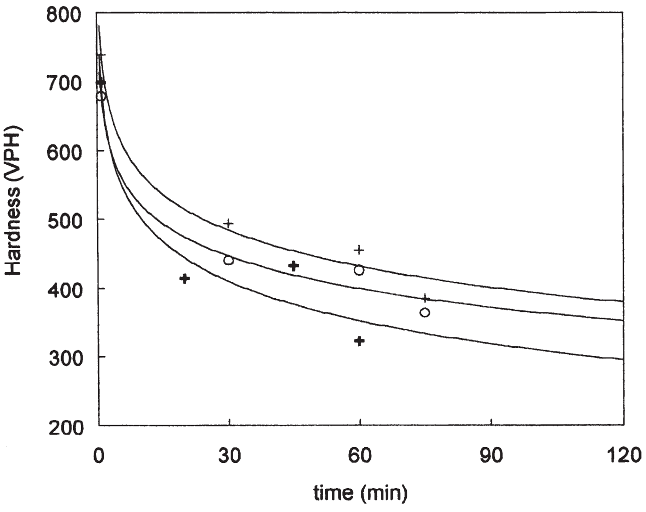

Figure 1: Tempering of steel armours at 350°C. Sample A is the light cross, B the open circle and C the heavy cross.

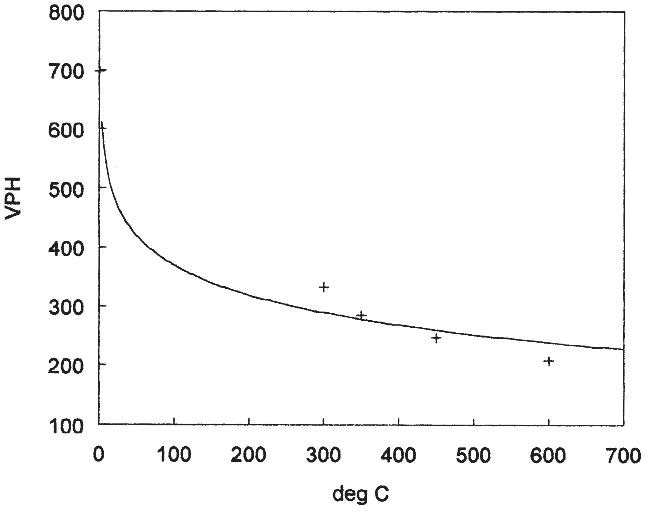

Figure 2: Hardness of sample C after tempering for one hour at various temperatures.

because of the absence of alloying elements such as manganese, nickel, and silicon. Manganese is not generally present in medieval steels at all; at least, the author has never found any in armour, except in slag inclusions (Williams 1991). In addition it should be noted that the data published by Grange (1977) were generally obtained from 2.5mm sections, thicker than these specimens of armour. It is possible that blueing, *ie* controlled oxidation, might have led to surface decarburization which played a part in the loss of hardness, although the photomicrographs (Figs 3, 4 and 5) show very little.

Discussion

There was a large and profitable market in making suits of armour which developed first in 14th century Milan, and then in the 15th century extended to Germany and the rest of western Europe. Armour of the best quality was usually made of steel (albeit a heterogeneous one) and the armourer endeavoured to improve its performance by judicious heat-treatment. Full-quenching risked not only quench-cracking of the steel but also warping the thin curved shells and tubes which made up suits of armour. Many armourers, especially the Milanese, preferred to slack-quench their products (Williams 1986). That is to say, instead of aiming for an all-martensite microstructure by fully quenching the steel and then tempering it afterwards, they delayed or interrupted their quench so as to give a microstructure which was a mixture of martensite, ferrite and pearlite (often in the nodular form formerly known as troostite). The hardness would be inferior to an all-martensite microstructure but the slower overall rate of cooling would much reduce the risk of cracking or warping. Such procedures survived into the 20th century, and were sometimes known as 'time-quenching' (Burns 1940).

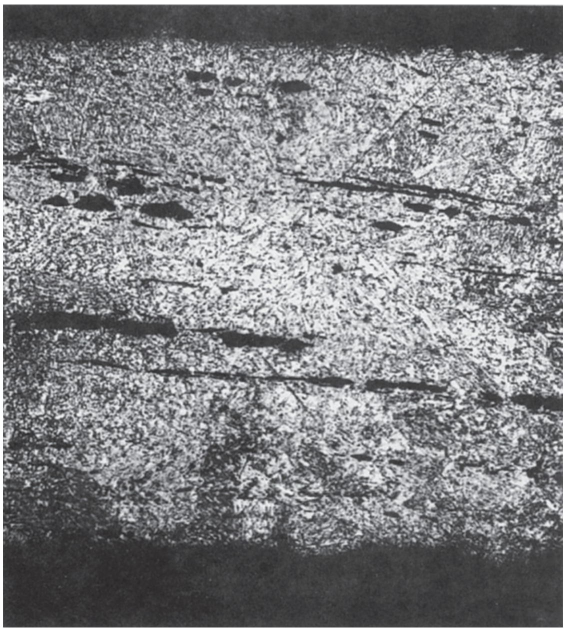

Figure 3: Sample A (Italian armour) after quenching and tempering for one hour at 500°C (x100)

Figure 4: Sample B (German armour) after quenching and tempering for one hour at 500°C (x100)

Although deprecated today, such cautious practice is understandable in the absence of any accurate means of measuring temperature, time, or carbon content (even were that to be constant). One consequence, however, of practising slack-quenching would have been that Italian armourers would not have had the requirement to develop expertise in tempering.

On the other hand, during the late 15th century many armourers in Germany (especially the production centres for princely armour of Augsburg, Innsbruck and Landshut) and later in England (the Royal workshop at Greenwich) mastered the more difficult art of fully-quenching followed by tempering. However, from around 1490-1510, a demand developed for gilded decoration to be applied to the armour, irrespective of any effect that fire-gilding might have on the hardness of the steel. After about 1510 Italian armour is almost never heat-treated to harden it, while the best craftsmen in Germany and England (under German leadership) were able to combine both hardening and fire-gilding. Mastery of these combined procedures seems to have been restricted to South German (and German-influenced) centres of armour production. By

Table 2: Mechanical properties of armour samples

Sample	A	B
Yield stress (MPa)	107	132
Ultimate tensile stress (MPa)	426	513
Elongation (%)	40	19
Young's modulus (GPa)	130	105.6
Vickers Pyramid Hardness (kg/mm^2)	183	514
Specific work of fracture (kJ/m^2)	200	532

Specific work of fracture was determined (by an opposed-wedge test) as the total work of fracture per unit cross-sectional area.

contrast, Italian armour of the 15th century was regularly made of steel and hardened by heat-treatment (Williams 1986), but by the 16th century it was made of steel of comparable carbon content decorated by gilding but now unhardened (Williams in press).

The precise sequence of operations must remain uncertain, but it seems probable that gilding (and blueing) followed quenching and tempering. There were evidently two heatings, since an incomplete Greenwich armour component dating from the early 17th century was found to be ungilded but tempered (Williams and de Reuck 1995, specimen number 59; it was unfortunately not possible to undertake microhardness measurements on this specimen).

I have argued elsewhere that this was only possible by the careful manipulation of the necessary operations in the right order requiring at least some co-operation between armourers and gilders (Williams and de Reuck 1995, 31). It has recently been suggested that gilding could have been an entirely separate operation because the necessary heating would not have affected the steel in any way (Anheuser 1997, 39). However, I believe that with the very low manganese contents of the steels employed, the reheating for gilding would have caused some fall in hardness. This may not have been a problem if the same man, or team, was responsible for all of these operations; the tempering could have been stopped at an earlier stage to allow for the heating that gilding and blueing required. But if the decoration was carried out as an afterthought, then the armour would be overtempered.

This may well help to explain why Italian armour, although frequently hardened in the 15th century, and frequently gilded in the 16th, is seldom, if ever, both hardened and gilded.

Appendix 1: Mechanical properties

It may be of some interest to quote mechanical properties determined for these specimens of armour (see Table 2)

Figure 5: Sample C (pseudo-medieval steel) after quenching and tempering for one hour at 500°C (x70)

since such data is not generally available. Indeed, it was only a fortuitous circumstance that provided the author with the exceptionally large (in historical terms) specimens which enabled such experiments to be carried out at all.

Appendix 2: modern fire-gilding

Although there is no guarantee that the precise details of the process have not changed since the 16th century, it may be of some interest to describe the process of fire-gilding as currently carried out beyond the United Kingdom.

The amalgam was made by chopping up gold foil into rectangles, twisting their ends to keep them apart and filling a crucible with them. Then it was heated, adding mercury as necessary and the mixture poured into cold water to granulate it.

After degreasing and polishing with liquorice root (sic) and water using a brass brush, the steel was put into spent pickle (acidic copper sulphate solution) until the colour was uniform. It was then brushed again.

The amalgam (which had separated on standing, and appeared liquid) was warmed again in the crucible and poured into water; the amalgam now had a solid appearance but was as soft as toothpaste. The surface was prepared with a solution of mercury in nitric acid (0.5% by volume) and the amalgam brushed onto the plate. The mercury was evaporated slowly (5 minutes or more) for a secure connection; it was allowed to cool and polished with a brass brush. Then it was heated for another minute, and finally burnished with a hematite stone.

Note that heating to blue the steel does not remove the gilding, but if overheated, its colour will be modified to a more orange-yellow colour (almost that of red gold) but a second gilding on top of first gives yellow colour again. Heating in the absence of copper (*eg* onto silver) will also alter the colour of the gilding so the cause may be loss of mercury or a change in surface porosity, rather than simply alloying with copper.

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The author

Alan Williams graduated in chemistry in 1964, and a fascination with the origins of chemistry developed into an interest in archaeometallurgy. Over the last twenty years he has published numerous papers on the history of technology and especially on the metallurgy of armour.

Address:
Department of Engineering, Reading University, Reading RG6 6AY.
E-mail: A.R.Williams@reading.ac.uk