HEAT TREATMENT OF HIGH SPEED STEEL

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High speed steel is a versatile material whose properties can be adjusted through heat treatment. The objective of this brochure is to show how heat treatment parameters can be selected and optimized in order to get the best combination of material properties, in particular with respect to hardness and toughness.

For convenience, the brochure has been divided into two sections. The first section – Basics – presents some metallurgical information which is necessary for a proper appreciation of the recommendations given in our product datasheets and in the second part of this brochure. The second section – Practical Recommendations – gives practical recommendations adapted to the chosen heat treatment technique, to ensure optimal heat treatment of HSS and ASP®.

CONTENTS

BASICS
- Heat treatment cycle 4
- Austenitising 5-6
- Quenching 7-8
- Tempering 9-10
- Distortion 11

PRACTICAL RECOMMENDATIONS
- Vacuum heat treatment 12-13
- Salt bath heat treatment 14-15
HEAT TREATMENT CYCLE

Material delivered by Erasteel is most often in a soft-annealed condition. This has been achieved by a specific heat treatment aimed at softening the material to make it suitable for soft machining operations such as turning and milling. In this state the material is far too soft to be used as a tool or component and a hardening heat treatment should therefore be applied to it after machining to give it the desired final mechanical properties. Due to their high alloy content, high speed steels require a specific hardening procedure schematically represented below and consisting of three stages:

- Austenitising (with 2 or 3 preheating steps before the austenitising itself)
- Quenching
- Tempering (at least two times)

These three stages are described in detail in the following parts of this section. The emphasis is on showing the effect of heat treatment variables on the material properties, as shown in the microstructure and on the measured mechanical properties (mainly hardness and toughness).

AUSTENITISING

SOFT-ANNEALED CONDITION

HSS is supplied in the soft-annealed condition. The structure consists of a ferritic matrix containing primary carbides and also smaller carbides which are formed during the soft-annealing process.

For control of the material temperature in the heat treatment process a “dummy” shall be used. It is important that the dummy

Carbide Dissolution

When the steel is heated to the austenitising temperature the following happens:
- The ferritic matrix is transformed to austenite.
- Carbides dissolve in the austenite.

The carbide dissolution provides the austenitic matrix with carbon and alloying metals which creates the potential for secondary hardening.

AUSTENITISING TEMPERATURE

The amount of carbides dissolved will influence the final hardness reached. A higher temperature will lead to more carbide dissolution and a higher final hardness. There is, however, an upper limit to the austenitising temperature which can be used.

If the temperature is higher than the maximum specified for the grade, see example in Figure 1 and datasheets, the hardness will continue to increase but there will be a very severe reduction in the toughness of the steel due to overheating, i.e. melting at the grain boundaries.

For control of the material temperature in the heat treatment process a “dummy” shall be used. It is important that the dummy

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*Figures given for ASPAPZ10 after tempering 3x1h at 520°C; consult ASPXAPZ10 datasheet for application specific tempering recommendations.
EQUILIBRIUM AND HOLDING TIME
Dissolution of carbides does not continue indefinitely at the austenitizing temperature. After a certain amount of time, an equilibrium condition will be reached between the carbides and the matrix. The matrix composition at equilibrium for ASP®2023 at different austenitizing temperatures is shown in Figure 2. A minimum amount of time will be required to reach equilibrium at a given austenitising temperature.

THE EFFECT OF INCREASING HOLDING TIME
Basically there is no point in increasing the holding times beyond those given in Figure 3. Once equilibrium is reached no further carbide dissolution takes place. The final hardness should be fixed by the austenitizing temperature and sufficient holding time to reach equilibrium.

OVERTIMING
A question which is frequently asked is whether overtiming leads to grain coarsening and loss of toughness. The effect of holding time on the bending properties for ASP®2023 is shown in Figure 4. It can be seen that for holding times up to 30 minutes, the bending strength and hence toughness are not affected at all. Normally, holding times are in the range 2 - 5 minutes so that 30 minutes represent a gross overtiming. For holding times in excess of 30 minutes a slight reduction in bending strength/toughness can be expected.

Figure 5 (page 7) shows the effect of austenitising temperature on the retained austenite content in ASP®2023 and ASP®2030.

COOLING RATE
The cooling rate is a very important factor in the heat treatment of high speed steels. Ideally, the cooling rate should be so rapid that the equilibrium reached at the austenitising temperatures is “frozen in” right down to the point where the steel is removed from the cooling medium for tempering. A proper tempering of the steel in this state would lead to optimal toughness and hardness. In practice, there is a divergence from the cooling rate needed to freeze in the equilibrium as that would mean zero cooling time. The effectiveness of the cooling will decrease with increasing size of the part being quenched. It is also very dependent on the efficiency of the cooling medium.

PRO-EUTECTOID CARBIDES (PEC)
It has already been seen in Figure 2 that the carbide dissolution in the austenite matrix increases with increasing temperature. Thus, as the temperature decreases during quenching, there will be a tendency for re-precipitation of carbides in the austenite matrix. The driving force for the precipitation will increase with decreasing temperature but the diffusion process by which the precipitation takes place will slow down with decreasing temperature.

The result is that the rate of precipitation reaches a maximum at around 950°C for HSS or, in practical terms, the critical cooling rate lies between 1000°C and 800°C.

The curves in Figure 6 have been obtained by heating samples to 1180°C and then transferring quickly to temperatures between 1050 and 800°C and holding for various times. After that, the samples have been quenched, tempered and the hardness measured.

As can be seen, the hardness markedly decreases with increasing time in this temperature interval. The pro-eutectoid precipitation has two undesirable effects:
- It depletes the matrix of carbon and alloying elements and thus lowers the potential for secondary hardening during tempering.
- It reduces the toughness of the hardened and tempered steel.

It is, therefore, essential to cool HSS with a high enough cooling rate through the range 1000 - 800°C to avoid loss of hardness and toughness after tempering.

Fig 6. Hardness vs temperature and time. Austenitising temperature: 1180°C. Tempering: 3 x 1h at 560°C.

Fig 2. Concentration of the alloying elements in austenite at equilibrium (ASP®2023).

Fig 3. Recommended holding times for HSS.

Fig 4. Bend test values for ASP®2023 austenitised at 1150°C using different holding times.

Fig 5. The effect of austenitising temperature on the retained austenite content (before tempering) in ASP®2023 and ASP®2030.

Fig 6. Hardness vs temperature and time. Austenitising temperature: 1180°C. Tempering: 3 x 1h at 560°C.
EFFECT OF PEC ON FINAL HARDNESS

The effect of pro-eutectoid precipitation on the hardness of the hardened and tempered steel is shown in Figure 7. Here, the final hardness is shown for various cooling rates between 1000 and 800°C. It is clear from the curves that a cooling rate of at least 7°C/second is necessary to avoid loss of hardness.

EFFECT OF PEC ON TOUGHNESS

The effect of pro-eutectoid precipitation on the toughness of the hardened and tempered steel can be seen in Figure 8. Here the fracture energy in bending (for ASP®2023) has been taken as an indication of the toughness. The reference line in Figure 8 shows the fracture energy versus hardness by varying the hardening temperature for a cooling rate of at least 50°C/second between 1000 and 800°C. Here the cooling rate is high enough to ensure that very little PEC is precipitated. Thus the reference line can be regarded as the line showing the maximum toughness that can be reached for a given hardness. Lowering of the cooling rate in the range 1000 - 800°C will cause a drop in hardness, and toughness, as shown by the line for a cooling rate of 2°C in Figure 8.

QUENCHING TEMPERATURE

The austenite structure begins to transform to martensite as the temperature is decreased below about 300°C (specific temperature can vary depending on grade and austenitising conditions). The transformation continues as the temperature decreases. The quench should go on until the parts have reached a temperature below 50°C, before beginning the tempering operation. Discontinuing the quench or starting the tempering while the parts are at a higher temperature, and the transformation to martensite has not proceeded as far as intended, can result in more retained austenite in the microstructure, leading to unexpected results in tempering.

AS QUENCHED STRUCTURE

The as quenched structure consists of a matrix of untempered martensite and retained austenite and undissolved carbides. Proeutectoid carbides are always more or less present in the former austenite grain boundaries: it is the PEC that make the grain boundaries visible after quenching, see Figure 8. The grain boundaries are more heavily underlined when there is more proeutectoid precipitation i.e. with a slower cooling. With extremely slow cooling, proeutectoid carbides will even start to precipitate within the grain boundaries.

Due to its high alloy content, high temperature austenite does not fully transform into martensite upon quenching to room temperature and as much as 40% of retained austenite can be found in the structure after quenching, see Figure 5 (page 7); hence the need for tempering.

TEMPERING

Tempering is made in order to achieve better properties by secondary hardening of the martensite by precipitation of very small (nano-size) carbides and, at the same time, conditioning the retained austenite to transform into martensite on cooling.

This new martensite must also be tempered (i.e. made less brittle), which is the reason why HSS must always be tempered at least twice. The tempering could be made in many different ways. However, the recommendation is to always temper at 560°C holding the steel at temperature for one hour minimum, two or more times, depending on steel grade.

TEMPERING TEMPERATURE AND TIME

For the same austenitisation temperature, the same hardness can be obtained in numerous ways by varying the tempering temperature and time. If a low tempering temperature is used, a long time must be used, and vice versa. However, the best properties are achieved by tempering at 560°C for one hour. The same hardness can also be achieved by varying the austenitisation temperature and the tempering temperature. The result of these two different ways to vary the hardness is shown in Figure 9. It is clearly seen that the best properties are obtained when the austenitisation temperature is varied and the tempering is carried out at 560°C. In addition, Figure 10 (page 10) shows that tempering below 560°C also gives inferior properties. At higher tempering temperatures than 560°C, shorter times must be used. However, this requires strict control of temperature and time during the whole cycle and in the whole charge, since overtempering (lower hardness and worse mechanical properties) accelerates above 560°C. For batch tempering only, 560°C is recommended otherwise there is a risk of both over and undertempering, since the outer of the charge will stay at temperature longer than the inner, which in turn may not reach temperature and thus become untempered. Tempering temperatures below 560°C need extended time in order to give acceptable properties.

NUMBER OF TEMPERINGS

During the first tempering, the untempered martensite is tempered and at the same time the retained austenite is conditioned to transform to martensite during cooling after tempering. The conditioning rate of the retained austenite depends on the tempering temperature as is shown in Figure 11 (page 10) where the amount of retained austenite for ASP®2023 grade is shown after each tempering for different tempering temperatures. The temperature between temperings should be allowed to reach room temperature (25°C) in order to make the transformation as complete as possible. The new untempered martensite must also be tempered, which is achieved with the second and third temperings; high speed steel should thus be tempered at least twice.

For most grades more than two temperings are needed to transform all retained austenite and untempered martensite to tempered martensite and a general recommendation is 3 temperings at 560°C. The effect of multiple temper cycles on the microstructure can be seen in Figure 12 (page 10). For grade specific recommendations, see Erasteel data sheets.

Fig 7. Effect of cooling rate between 1000 and 800°C on final hardness. Austenitisation temperature: 1180°C. Tempering: 3 x 1h at 560°C.

Fig 8. Effect of PEC on the toughness. ASP®2023 tempered 560°C, 3 x 1h. (Structure after hardening, before tempering).

Fig 9. Un-notched impact toughness for ASP®2023.

Fig 10. Relationship between austenitisation temperature and number of temperings.
DISTORTION

PHASE TRANSFORMATION AND VOLUME CHANGE

When ferrite transforms into austenite during heating the volume decreases because the austenite lattice is more dense than the ferrite lattice. When the austenite at cooling transforms into martensite below 200°C the volume increases again and more than the original ferrite. At tempering, the volume decreases again, however not fully back to the original ferrite so that, at the final stage, there is an increase in volume compared to the original state, Figure 13.

If the temperature is uneven so that the transformations occur at different parts of the tool at different times, this may result in distortion. For instance, if one side is cooled faster than the other, the martensite transformation starts earlier on that side and the volume increases and will then bend the piece because the austenite in the other side is soft. When the other side transforms to martensite it will not be able to bend back the piece since the first transformed side is then hard. Consequence is a bent piece or even cracked, since untempered martensite is brittle.

Temperature gradients are impossible to avoid, there is always a difference between surface and core. However, the general rule is to keep the gradient as symmetric as possible.

For very large parts, it can be recommended to step quench (by first quenching down to a temperature between 600°C and 500°C and holding for some time) in order to homogenize temperature, this way limiting the thermal gradients and reducing the risk of cracking. It can also be useful, for big parts, to stop the quenching when the temperature reaches 50°C and not allow the part to cool further down before the first tempering. The risk of cracking due to thermal gradients is higher when quenching in salt bath due to the very high cooling rates obtained.

THERMAL STRESSES

Stress may arise due to uneven temperature, even if there are no transformations. The consequence and recommendations are the same as above.

MACHINING STRESSES

These are created due to deformation of the surface during turning, milling, etc. When the piece is heated, these are released and may then lead to distortion.

SUB ZERO TREATMENT

If the tempering is correctly made, i.e. the tools are cooled down to below 25°C between the temperings, and tempered at the correct temperature, 560°C at least 1 hour each time, then a sub zero treatment is unnecessary and only an extra cost.

If it is not possible, for example of climate reason, to reach the 25°C between the temperings, a sub zero treatment can be a solution. However, in order not to lose hardness and not to risk cracking, the sub zero treatment should be made between the first and the second temperings.

SUB ZERO TREATMENT

Fig 10. Impact and bend strength for ASP® 2030. Austenitised at 1180°C. Tempered 3 x 1h.

Fig 11. Retained austenite content in ASP® 2023, austenitised at 1180°C, as a function of tempering temperature and number of tempers.

Fig 12. Effect of tempering on the appearance of the microstructure.

Fig 13. Volume change during hardening.
AUSTENITISING

Before the final stage, the nitrogen is pumped out to about 1 mbar. This small pressure is of benefit in minimising the risk of chromization. If the pressure is lower, there is risk of chromization and welding. The holding times given in Figure 3 (page 6) can be used.

QUENCHING

Particular attention must be paid to the cooling rate to minimise the pro-eutectoid carbide precipitation as outlined in the Basics chapter. The factors affecting the cooling rate in a vacuum heat treatment furnace in addition to the wall thickness/diameter of the pieces, are:

- Gas pressure
- Gas direction
- Gas velocity
- Gas temperature

These factors are inherent to the design of the furnace. Other factors are type of gas (usually nitrogen for cost reasons), the size of the charge, and how the charge is built up. There might be a difference at different positions in the furnace.

TEMPERING

Even though it is possible to temper in a vacuum furnace, it is normally too costly and capacity demanding. Tempering is preferably made in another simpler furnace. If tempering, however, is made in the vacuum furnace, attention should be paid to the temperature between tempers which should be about room temperature (25°C). It is best to remove the charge and let it cool outside the furnace between tempers.
The cooling rate and hence final hardness decrease with increasing diameter, as shown in Figure 18. Here it can be seen that there is a measurable decrease in hardness (at the centre of the cylinder) for specimens with a diameter larger than ~40 mm. This corresponds to a cooling rate (at the centre of the cylinder) of around 7°C/second, which is the minimum cooling rate needed to prevent a measurable loss of hardness (see Figure 7 - page 8). Cooling should be made down to about 40 - 50°C. If cooling is interrupted earlier, there will be too much retained austenite left and cooling to lower temperatures may cause cracking.

**TEMPERING**

Tempering should be carried out two or more times at 560°C and the holding time at tempering temperature should be one hour. The parts must be cooled down to room temperature (i.e. <25°C) between the temperings in order to ensure complete transformation of the retained austenite.

**CONVERSION TABLE °C TO °F**

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**SALT BATH HEAT TREATMENT**

**PRACTICAL ADVICE**

In order to minimise the distortion, it is of utmost importance that the tools are hung correctly. Long pieces should not be allowed to deform under their own weight, i.e. they should not be put in a basket but tied with a wire and hung directly in the bath. If a fixture is used, the fixture must be in very good condition so that the tools are hanging exactly straight in the bath. Moving long tools between the baths must be carried out with extreme care for avoiding bending of the tools due to careless handling.

Tools with high demands on straightness should be protected from all kinds of draft during quenching when the austenite transforms into martensite (below 200°C) by for example putting the tools in a barrel.

A typical temperature cycle for a salt bath heat treatment is shown in Figure 15.

**PRE-HEATING**

Pre-heating should be carried out in 2 or 3 steps 450°C, 850°C (and 1050°C) to minimise distortion.

**AUSTENITISING**

The austenitising temperature required for the final hardness is selected using table on page 5. The total soaking time depends on the wall thickness and the austenitising temperature used. As examples, the wall thickness will be the diameter of a solid, long tool, and the thickness of a flat disc. The total soaking time in the austenitising bath can be obtained for different wall thicknesses from the curves given in Figure 16. Note that these curves are indications only and that adjustments need to be made to take into account the part geometry and salt bath characteristics.

**QUENCHING**

The part to be hardened is quenched in a salt bath at about 550°C. This ensures rapid cooling through the temperature range 1000 - 800°C and temperature equalisation before transformation to martensite occurs (when the part is removed from the bath and allowed to cool in air). The cooling rate in the range 1000 - 800°C reachable with a salt bath at 550°C is shown in figure 17 for cylindrical ASP®2023 samples with different diameters.

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