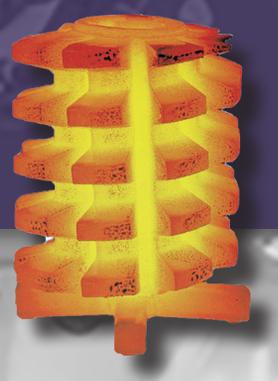
ERASTEEL

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 in 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

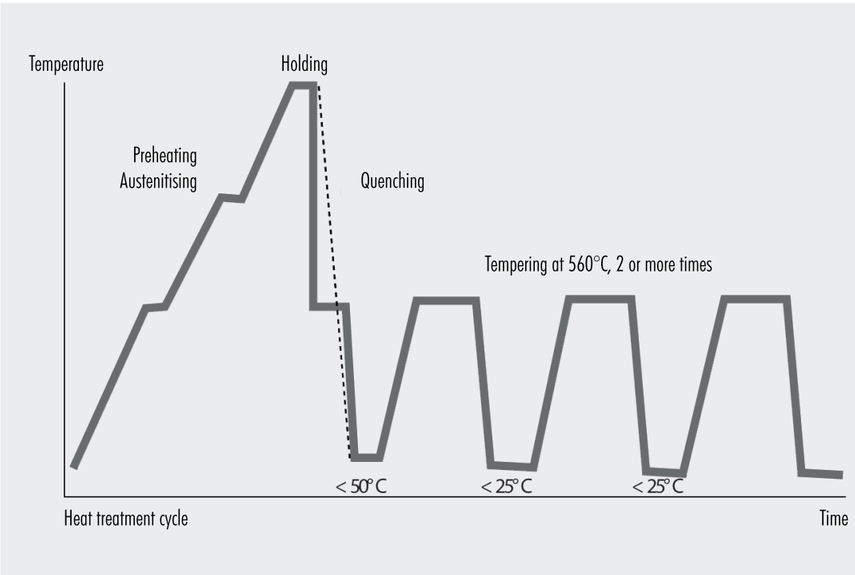
PRACTICAL RECOMMENDATIONS

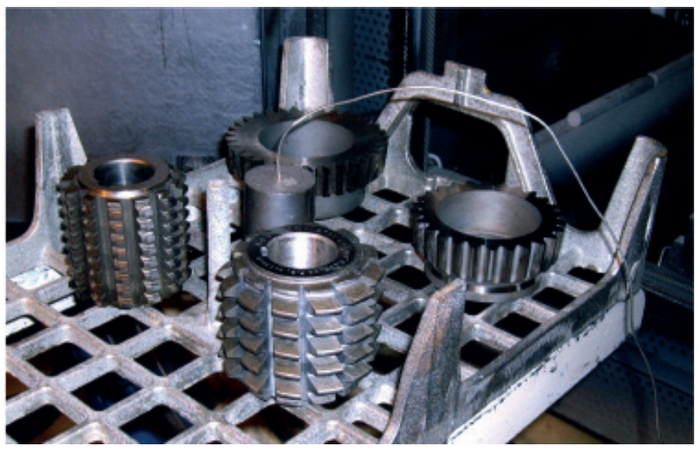
HEAT TREATMENT CYCLE

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:

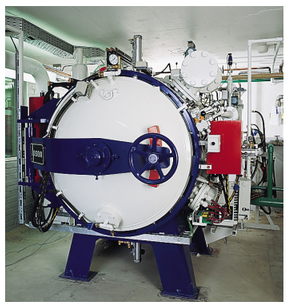
- Austenitising (with 2 or 3 preheating steps before the austenitising itself)
- Quenching
- Tempering (at least two times)

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).





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



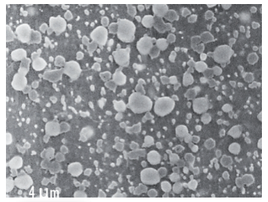
Vacuum furnace

ASP® is a registered trademark of Erasteel

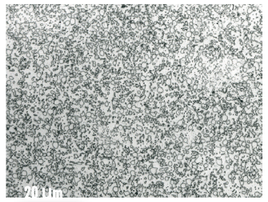
AUSTENITISING

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.



Soft annealed structure.
SEM-picture, 5000 X.



Soft annealed structure.
LOM-picture, 1000 X.

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.

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.

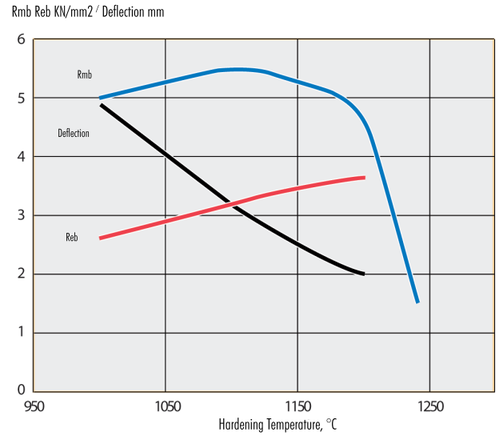


Fig 1. Bend test of ASP 2023 versus hardening temperature.

ASP & HSS	Austenitising temperature, °C										Tempering 3 x 560°C						
HRC	50	52	54	56	58	59	60	61	62	63	64	65	66	67	68	69	70
ASP® 2004							1050		1100		1150		1180	1220			
ASP® 2005					1000		1050		1100	1150	1180						
ASP® 2009	1050	1100	1150	1200													
ASP® 2011		950	1000	1050			1120		1180								
ASP® 2012		1000	1050	1080	1110		1120										
ASP® 2015									1100		1150	1180	1220	1260			
ASP® 2017						1000		1050		1100	1150	1180					
ASP® 2023					1000		1050		1100			1150	1180				
ASP® 2030							1000		1050		1100		1150	1180			
ASP® 2042														1100	1150	1180	1210
ASP® 2048										1000		1050	1100		1180	1200	
ASP® 2052							1000			1100	1150		1200	1240			
ASP® 2053						1020		1070	1100		1150	1180					
ASP® 2055									1000		1050		1100	1150	1180		
ASP® 2060									950		1000		1050	1100	1150	1180	
ASP® 2078														1100	1150	1180	1210
ASP® APZ10					1060*	1080*	1095*										
BlueTap® Co							1050		1100		1150	1180	1220				
E T1								1150	1180	1220	1240	1270					
E M1								1100		1150		1180					
E M50										1080	1120						
E M2				1000	1030	1050	1075	1100	1125	1150	1180	1220					
ABC III								1100		1150	1180						
E M7									1100	1130	1150	1180	1200				
E M3:1										1150		1180					
E M3:2									1120	1150		1180	1220				
Grindamax V3									1120		1150	1180	1220				
E M4								1100		1150		1220					
E 945								1070			1120		1170				
E M35							1050		1100		1150	1180	1220				
C8										1050	1100		1150	1180	1200		
E MAT II									1050	1080	1100						
E M42										1050		1100		1150	1190		
WKE 42											1100		1180	1200	1230		
WKE 45												1100	1150	1180	1220		

*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.

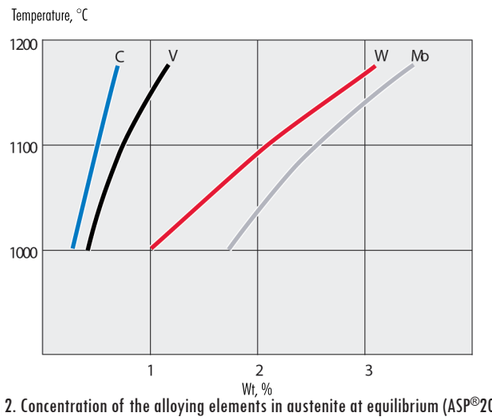


Fig 2. Concentration of the alloying elements in austenite at equilibrium (ASP®2023).

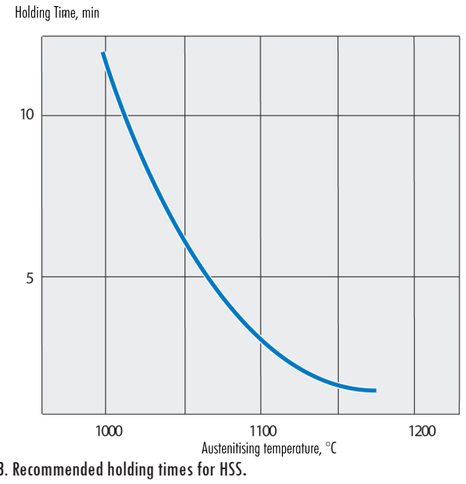


Fig 3. Recommended holding times for HSS.

The time to reach equilibrium is the holding time. The effect of austenitizing temperature on holding time is shown in Figure 3. The dissolution of carbides takes place by diffusion and the rate of diffusion increases with increasing temperature. The consequence is that a shorter holding time is needed to reach equilibrium at higher temperature, even though more carbides are dissolved.

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.

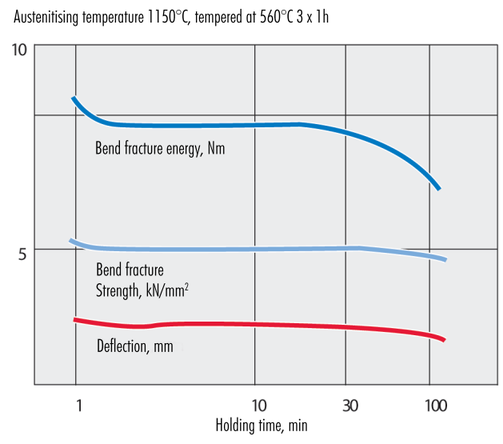


Fig 4. Bend test values for ASP® 2023 austenitised at 1150°C using different holding times.

QUENCHING

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.

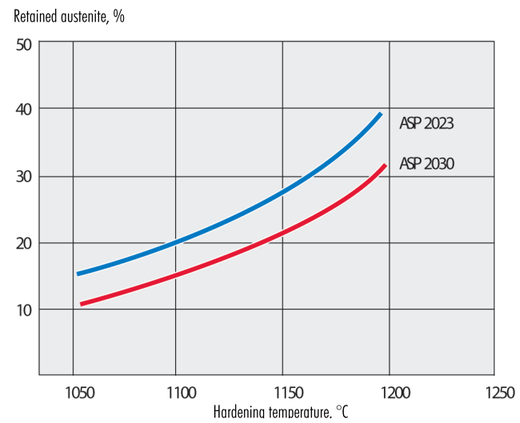


Fig 5. The effect of austenitising temperature on the retained austenite content (before tempering) in ASP®2023 and ASP®2030.

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.

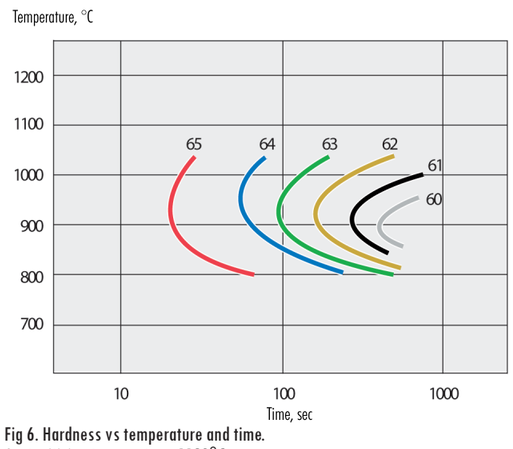


Fig 6. Hardness vs temperature and time.
Austenitising temperature: 1180°C.
Tempering: 3 x 1h at 560°C.

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/s 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.

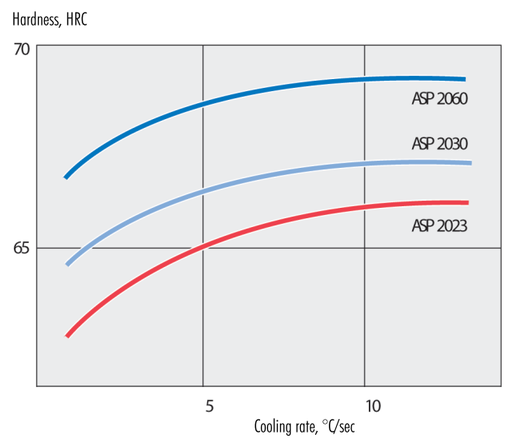


Fig 7. Effect of cooling rate between 1000 and 800°C on final hardness.
Austenitising temperature: 1180°C.
Tempering: 3 x 1h at 560°C.

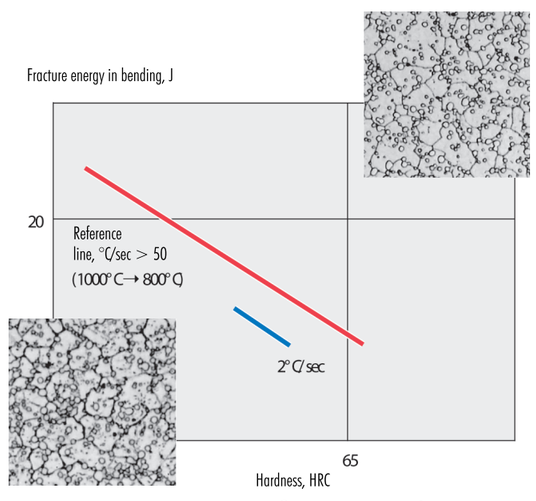


Fig 8. Effect of PEC on the toughness. ASP® 2023 tempered 560°C, 3 x 1h. (Structures after hardening, before tempering).

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 temperature 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 then become undertempered. 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.

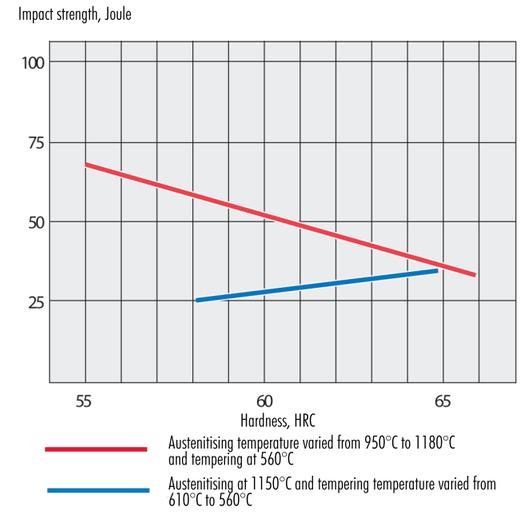


Fig 9. Un-notched impact toughness for ASP® 2023.

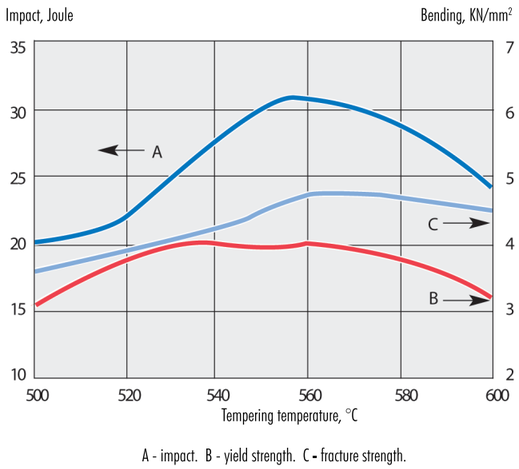


Fig 10. Impact and bend strength for ASP® 2030.
Austenitised at 1180°C. Tempered 3 x 1h.

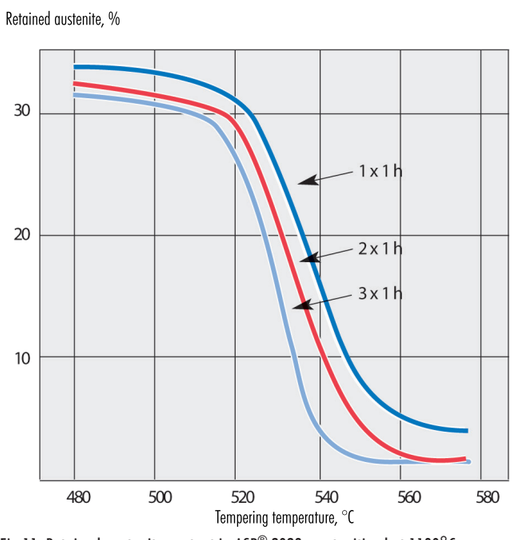


Fig 11. Retained austenite content in ASP® 2023, austenitised at 1180°C, as a function of tempering temperature and number of tempers.

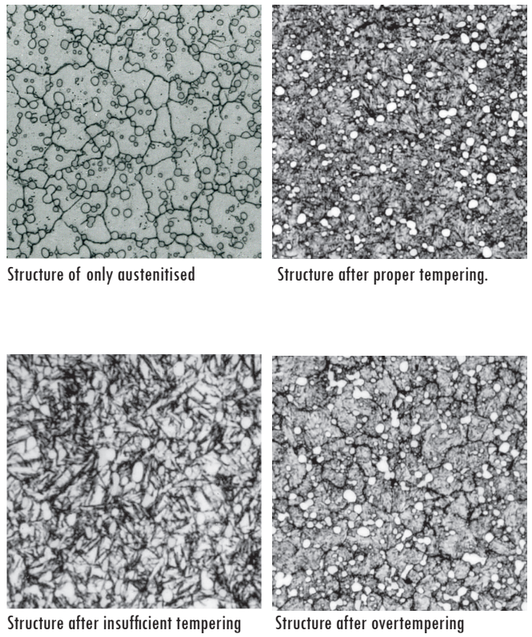


Figure 12. Effect of tempering on the appearance of the microstructure.

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.

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.

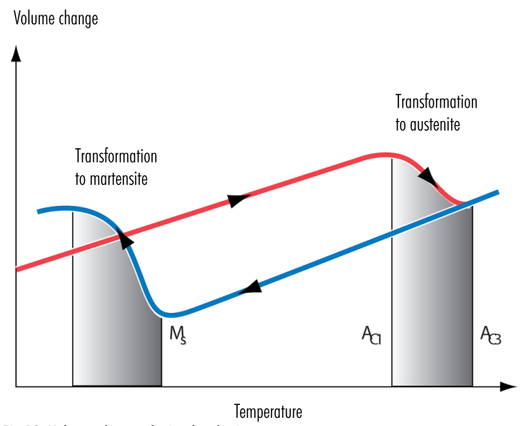


Fig 13. Volume change during hardening.

VACUUM HEAT TREATMENT

Vacuum heat treatment with gas quenching has now become the dominant process to harden HSS. It has the advantage over the traditional salt bath treatment that it is environmentally friendly, less costly to operate and easier to control. There are different designs of furnaces, however, typical features for modern single chamber furnaces are that heating up to about 800°C is made by gas (normally nitrogen) convection and then by radiation in vacuum up to the austenitising temperature. Quenching is then made by gas (normally nitrogen) with over-pressure at high gas velocity. The temperature cycle can be programmed and is controlled by a furnace thermocouple (for the heat supply) and charge thermocouple(s) to follow the actual temperature.

The best recommendation is, of course, to establish your own furnace practice from experience, however some general guidelines are outlined in the following.

A typical heat treatment cycle is given in Figure 14.

PRACTICAL ADVICE

In order to avoid distortion the main principle is to build up the charge in such a way that the gas can flow as uniformly as possible through the charge.

It is also very important to think of the gas speed, pressure and direction. Long pieces, for example, should not be allowed to deform under their own weight, i.e. they should preferably be hanging, however, they must be fixed in such a way that, during quenching, they are not whirling around in the furnace due to the gas speed.
It is also important that the charge is cleaned from cutting fluids and other dirt, because oil for example, can cause carburisation of the tool. The dirt itself is also detrimental for the furnace because it ends up in the oil, valves and damages the heat exchanger. Oxides on the surface of tools can create decarburisation, and, if tools are pressed too hard to each other, there is a big risk that the tools weld together.

PREHEATING

It is made up to about 800°C in convection. The demand on shape stability must be considered when determining the heating speed. The final heating can start when the interior of the charge is 40 - 60°C below the set temperature.

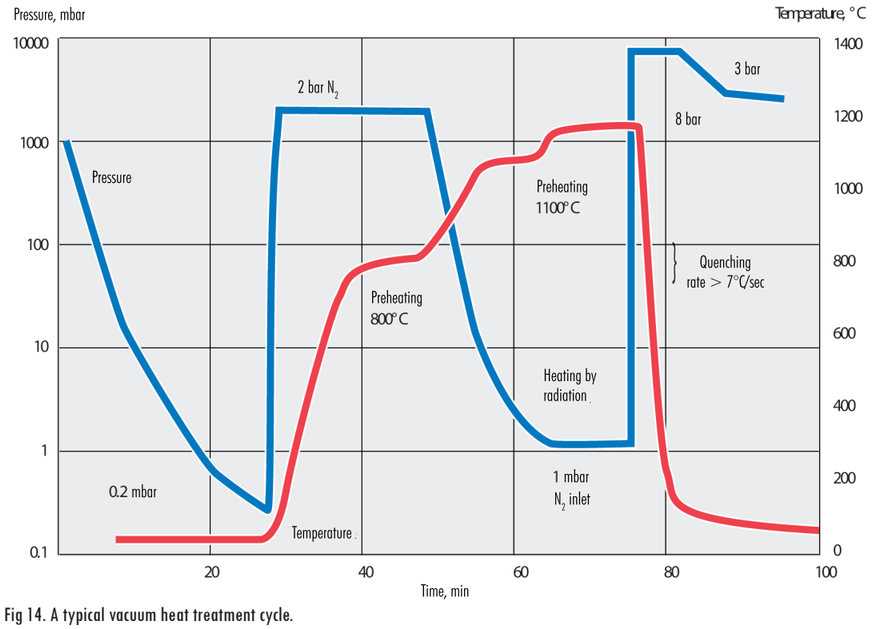


Fig 14. A typical vacuum heat treatment cycle.

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.

PROCEDURE FOR “MIXED” CHARGES

If a charge is made up of parts requiring different final hardness levels, a procedure with a high hardening temperature and tempering back to the hardness required (by using temperatures in excess of 560°C) is not recommended.

It has already been seen in Figure 9 (page 9) that this procedure results in a reduction in fracture energy and toughness. It is then no longer correct to assume that the parts with the lower hardness have the better toughness. The best way to deal with mixed charges is to separate the parts into various hardness groups.
For example, parts required to have a final hardness in the range 60 - 62 HRC could be hardened together to 61 HRC and those required to have a final hardness in the range 62 - 64 HRC could be hardened together to 63 HRC etc. Each group can then be hardened at the same temperature and tempered three times at 560°C. From the above it is clear that there is no point in specifying a final hardness if this hardness is achieved in the wrong way by not using the optimal tempering temperature. It is much better to select the austenitising temperature and to make sure that the cooling rate is optimal. The tool should then be tempered in the range 550 - 570°C and used at the hardness that results.

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.

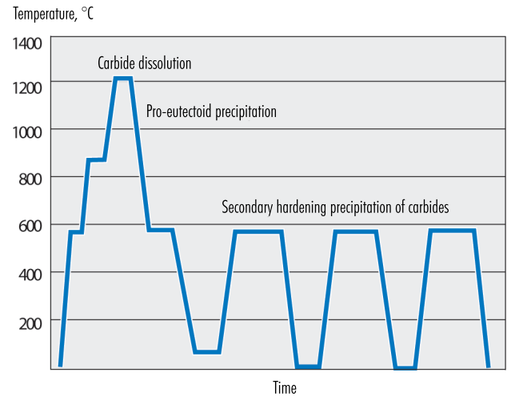


Fig 15. Salt bath furnace heat treatment cycle for the ASP® steels.

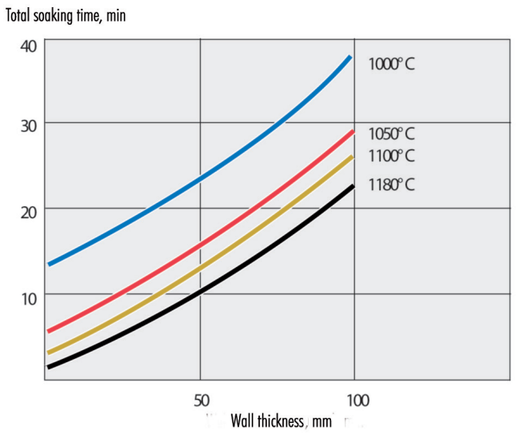


Fig 16. Total soaking time in salt bath after preheating in two stages at 450°C and 850°C.

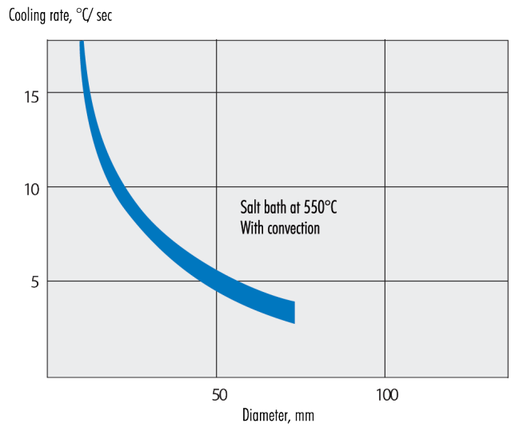


Fig 17. Cooling rate in the range 1000 to 800°C at the centre of cylindrical samples.

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.

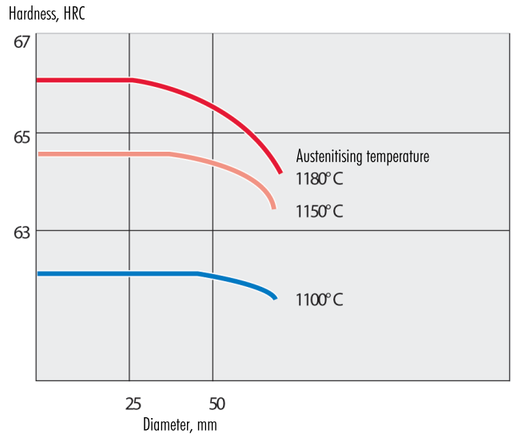


Fig 18. Hardness at the centre of cylindrical samples as a function of diameter. (Tempering 3 x 1h at 560°C).

CONVERSION TABLE °C TO °F

°C	°F	°C	°F
5	41	1000	1832
7	45	1020	1868
15	59	1030	1886
40	104	1040	1904
50	122	1050	1022
200	392	1060	1940
400	752	1070	1958
450	842	1080	1976
480	896	1090	1994
500	932	1100	2012
520	968	1110	2030
540	1004	1120	2048
560	1040	1130	2066
580	1076	1140	2084
600	1112	1150	2102
700	1292	1160	2120
800	1472	1170	2138
850	1562	1180	2156
900	1652	1190	2174
920	1688	1200	2192
940	1724	1210	2210
950	1742		
960	1760		
975	1787		

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