TENASTEEL ®P

Processing guide

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TENASTEEL®℗ SUMMARY OF PROCESSING GUIDE

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Conventional cold work tool steels very often showed their limits.

If most efficient of them (X160 Cr Mo V12 / D2 type) offer very acceptable wear resistances, they show however an excessive tendency to brittleness. This chronic lack of toughness will be all the more significant as steel will be heat treated to high hardnesses (58/62 HRC).

Everyone knows the traditional consequences of this weakness: breaking punches, chipping...

The extremely coarse structure of these grades can also induce other problems, such as bad EDM surface qualities (tools more sensitive to adhesion wear), polishing problems, poor adhesion of surface coatings...

The only alternative available in the range of conventional steels is the lower alloyed steels (X100CrMoV5, X38CrMoV5) : Their finer structure leads to a significant toughness increase. This improvement is unfortunately made to the detriment of wear resistance which, in this case, drops down to a level dramatically lower than that for a standard steel X160 Cr Mo V12 / D2.

In addition, tools are more and more often surface treated or coated, which enables steels to be exposed to thermal cycles at 500/580°C (*930/1080°F*) without significant drop in their mechanical properties.
Its standard chemistry does not confer to X160 Cr Mo V12 / D2 grade any particular aptitude in terms of resistance to softening.

To sum up, conventional grades very often offer a bad compromise between wear resistance / toughness / tempering temperature.

The need thus appears for a new generation of grades better suited to the current needs of toolmakers.

The new grade TENASTEEL® has been developed for that purpose and presents all the required properties :
- Wear resistance equivalent to X160 Cr Mo V12 / D2
- Fine structure without coarse carbides
- Toughness much higher than X160 Cr Mo V12 / D2
- Tempering temperature in the range 550/580°C (1020/1070°F)

Due to these combined properties TENASTEEL is a multi-purpose steel, efficient in many different applications facilitating thus enormously the job of the designers when they have to select adapted materials.

But the improvement of tools life and the reduction of down-time rates, during the tooling manufacture as well as in production, will yield the most significant profit.

The goal of this technical document is to detail the properties of TENASTEEL, as well as provide support and information for all the traditional operations of transformation, machining, heat treatment...

Produced from selected scrap, steel is melted in an electric arc furnace, then deoxidized and desulphurized. It is then vacuum refined, and chemical analysis is adjusted by the addition of alloying elements.
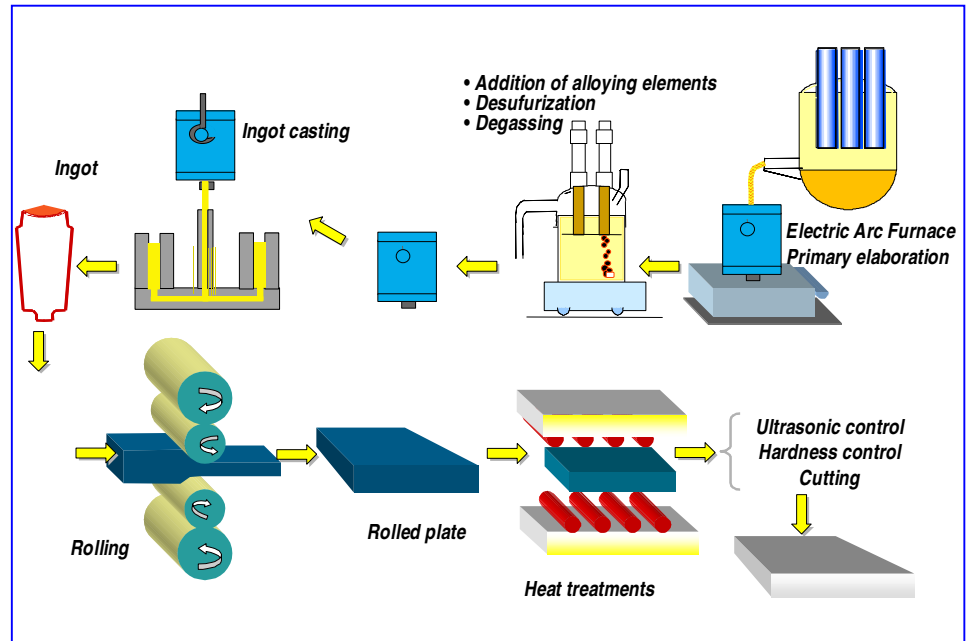
A degassing is then carried out to reach a low density of oxide and alumina inclusions, very close to ESR (electroslag remelted). Moreover, this operation ensures a very low hydrogen level to guarantee a sound finished product.

Systematic inspections are carried out at every stage of the production to ensure the conformity of the chemical composition and the temperature of casting. The shape of ingot moulds (bottom poured), is also optimized in order to improve the uniformity of material.

Then, ingots follow an optimized rolling program computer controlled to guarantee a good through thickness soundness, as well as a good surface quality.

Plates undergo an heat treatments cycle, mainly annealing and stress relieving at the final stage to release a maximum of residual stresses.

- **CHEMICAL ANALYSIS**
- **STRUCTURE**

	C	Mn	Cr	Mo	V	Others
X160Cr Mo V12 / D2	1.55	0.35	11.75	0.75	0.95	-
TENASTEEL®	**1.0**	**0.35**	**7.5**	**2.6**	**0.3**	**Ti**

The TENASTEEL® differs from standard grade X160 Cr Mo V12 / D2 by 3 main points

① *Low carbon - Low chromium*

High chromium and carbon contents always induce formation of coarse chromium carbides effective in term of wear resistance, but principal causes of brittleness in steel X160 Cr Mo V12 / D2 type.

The concentration of these large carbides will be even more intense at mid thickness of the products (segregated bands).

Conversely, lower levels of carbon and chromium guarantees
- a much finer carbide distribution, therefore better toughness
- a better uniformity in the thickness.
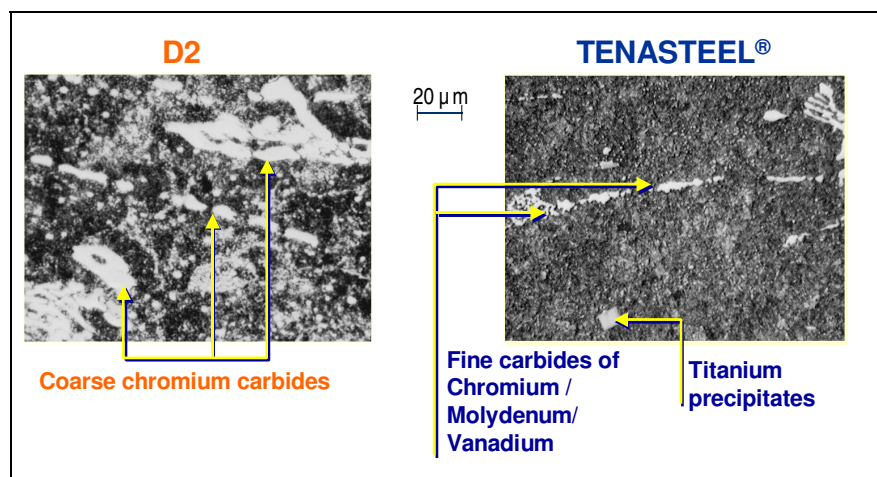
② *Content with molybdenum reinforced*

The molybdenum content of the TENASTEEL® has a double purpose :

- To compensate the lowering of chromium by formation of very hard molybdenum carbides (1800 HV) much finer and better distributed than chromium carbides of X160 Cr Mo V12 / D2.

- To increase the resistance to softening of the steel. During heat treatment, for the same tempering temperature of 550°C (1020°F), the hardness of TENASTEEL® will remain higher than that of X160 Cr Mo V12 / D2.
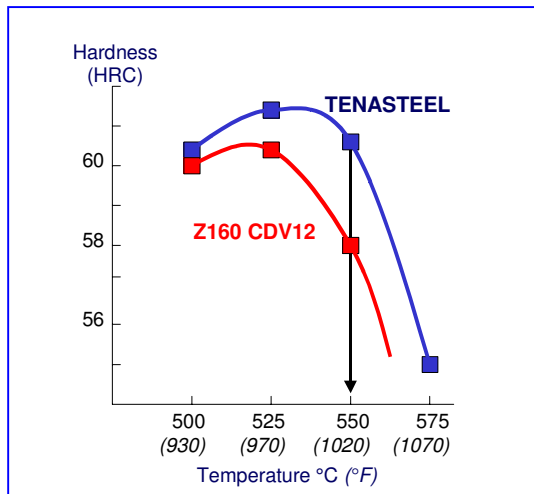
Due to this property TENASTEEL® is more adapted to coatings and surface treatments than conventional grade X160 Cr Mo V12 / D2.

TENASTEEL® achieves a high hardness with tempering temperatures of 550°C (*1020°F*).
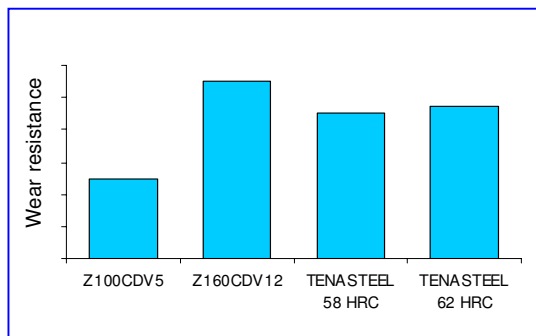
③ *Titanium addition*

It allows formation of very hard titanium carbides (3200 HV) which insure optimum wear resistance close to that of X160 Cr Mo V12 / D2.

Wear test per to ASTM G65

SUMMARY

In comparison with X160 Cr Mo V12 / D2, chemical analysis of the TENASTEEL® ensures

- **Equivalent wear resistance,**
- **Much higher toughness,**
- **Better ability to surface treatments and coatings.**

HARDNESS

① *As-delivered condition*

The grade is delivered in the annealed condition with a hardness of 250 HB maximum.

② *In heat treated condition*

TENASTEEL® can be heat treated by hardening and tempering with a hardness included in the range 58/62 HRC, with temperatures of austenitization between 1000 and 1050°C (*1830 and 1920°F*) and tempering temperature over 550°C (*1020°F*)

For more information on heat treatment parameters, please refer to chapter Heat Treatment.

TOUGHNESS

With a homogeneous distribution of fine carbides, the structure is particularly adapted to obtain a high level of impact strength after heat treatment.

The level of impact strength obtained will depend, of course, on a certain number of parameters such as hardness, or heat treatment conditions.

Following data are indicative values obtained at 20°C (*68°F*) on unotched specimens in the various described conditions.

① *Influence of austenitization temperature*
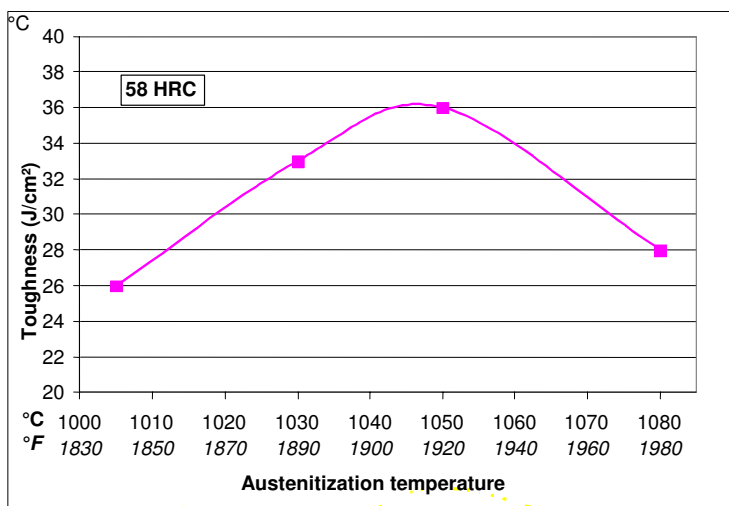
It is advised to avoid too high austenitization temperatures (grain coarsening) or too low temperatures (imperfect carbide dissolution) if one wishes to optimize impact strength of TENASTEEL®.

In this case, it is the range 1030°C/1050°C (*1880/1920°F*) which allows best possible optimization.

② _Influence of hardness_

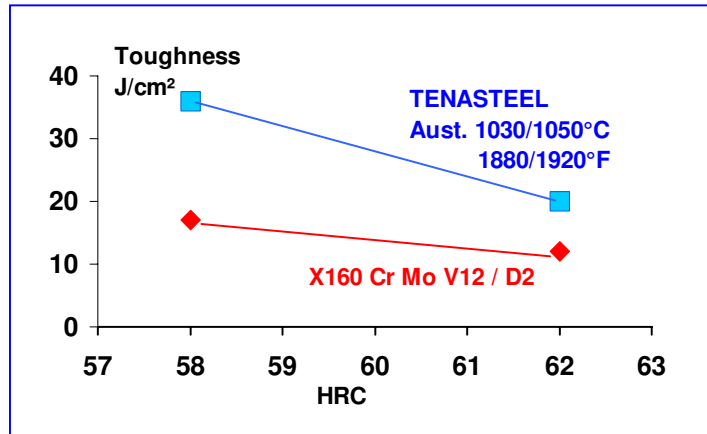The most influential parameter on toughness is in fact the hardness achieved during heat treatment. Whatever the level of hardness, toughness of TENASTEEL® will be always approximately double of that of X160 Cr Mo V12 / D2, at the same level of hardness..

WEAR RESISTANCE

Following data have been measured on heat treated specimens according to ASTM G65 D method. Its relative wear is compared to a reference 1 which X100 Cr Mo V5 / A2 steel.
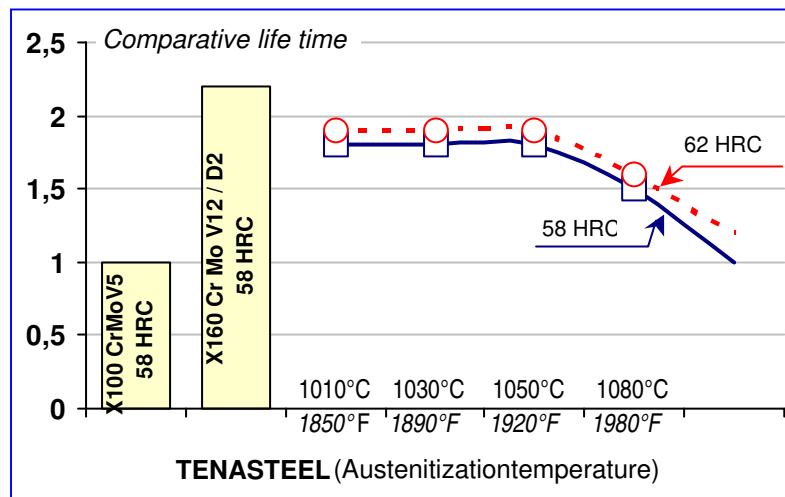
The wear resistance of TENASTEEL® is very close to that of X160 Cr Mo V12 / D2 and dissociates very clearly from grades type X00 Cr Mo V5 / A2

The level of hardness has a small influence on the wear resistance of TENASTEEL®. A decrease in wear resistance can be noticed for high austenitization temperatures (1080°C – _1980°F_) which confirms the optimum of temperature 1030/1050°C (_1880/1920°F_).

TENASTEEL®℗

Optimization toughness / tool life
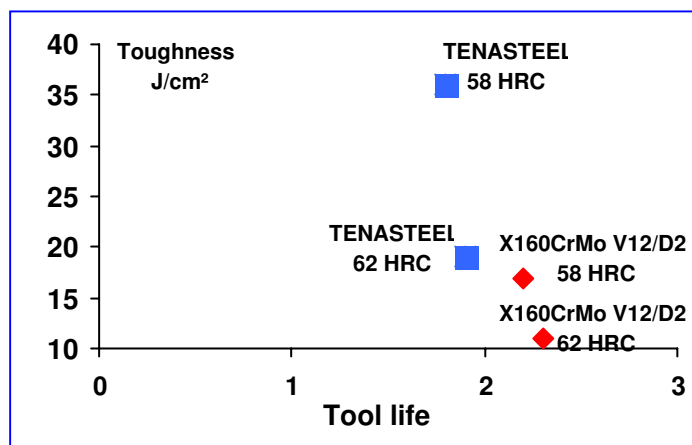
Thanks to TENASTEEL®, tool life can be optimized close to that of the X160CrMo V12 with a level of toughness twice higher.
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PHYSICAL PROPERTIES

- Density at 20°C (*68°F*) : 7.75

- Young Modulus : 205 000 N/mm²

- Thermal conductivity at 20°C (*68°F*) : 21 $W.m^{-1}.°K^{-1}$

- Typical thermal expansion coefficient between :
  20 – 100°C $10.2 \ 10^{-6}.°K^{-1}$
  20 – 200°C $11.3 \ 10^{-6}.°K^{-1}$
  20 – 300°C $11.9 \ 10^{-6}.°K^{-1}$
  20 – 400°C $12.8 \ 10^{-6}.°K^{-1}$

- Specific heat at 20°C
        460 $J.Kg^{-1}.°K^{-1}$

SUMMARY

- **Optimum properties are obtained with an autenitization temperature within 1030/1050°C.**
- **Whatever the level of hardness, TENSASTEEL® has always a double toughness level double that of X160 Cr Mo V12 / D2.**
- **Wear resistance of TENASTEEL® is very closed to that of X160 Cr Mo V12 / D2.**

INDUSTEEL
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Machining of cold work steels is an important operation, by the cost it represents and by the problems it may generate.

These incidents are not insolvable, they are generally illustrated by tool breakage or abnormally short tool lives, or by surface qualities locally disturbed.

Generally, such problems have a metallurgical origin : coarse carbides, with significant local concentrations.

These carbides will induce strong wear on cutting tools. The areas where maximum sizes and concentrations are found, frequently called hard spots, can lead to significant chipping, eventually tool breakage, especially for critical operations such as drilling.

As already mentioned, TENASTEEL® benefits from a fine structure with small micro carbides.

This structure plays a main role in the improvement of machining performance of TENASTEEL® when compared to grade type X160 Cr Mo V12 / D2.

Machined volumes are generally small, there is no advantage to look for high chip removal rate.

The improved machinability of TENASTEEL® will thus result mainly in an increasing tool live and in a reduction of incident rates.

PERFORMANCES BEHAVIOUR

Machining tests were carried out comparing TENASTEEL® to the X160 Cr Mo V12 / D2 in collaboration with ENSAM (Ecole Nationale Supérieure d'Arts et Métiers) in Cluny - France.

This comparison was carried out in annealed condition, and after hardening.

All tests were conducted with a SECO tool :
   - Octomill mill R220.43-0063-07W
   - Carbide inserts OFEN 070405TN-F30M-D18

■ **Tests in annealing condition**

Tests were conducted to compare tool lives in the same conditions, with same cutting parameters, for the 2 grades TENASTEEL® and X160Cr Mo V12 / D2.

Cutting conditions for this tests were :

Cutting speed	Vc = 100 m/min
Feed	fz = 0.15 mm/tooth
Radial depth	ae = 45 mm
Axial depth	ap = 2.5 mm

Results below confirm a lengthening of tool life of 25% minimum, depending on accepted tool wear.
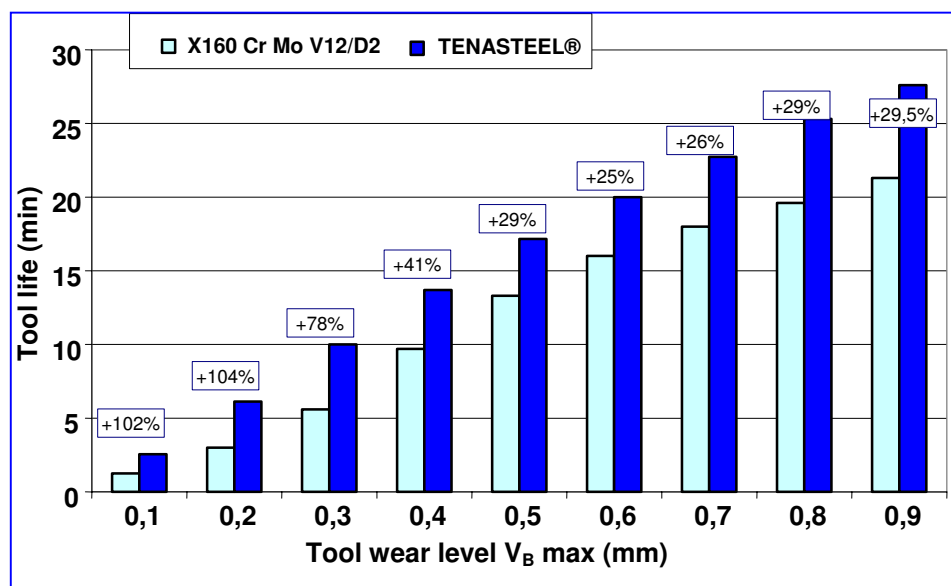
■ **Tests in heat treated condition**

The same test procedure has been used. Before machining, both grades have been heat treated to 58 HRC by hardening and double tempering.

Of course, machining parameters have been reduced :

Cutting speed	Vc = 30 m/min
Feed	fz = 0.2 mm/tooth
Radial depth	ae = 45 mm
Axial depth	ap = 0.3 mm

In hardened condition, tool life increase is even more significant than in softened condition since tool life increases by 70% in favor of TENASTEEL®.
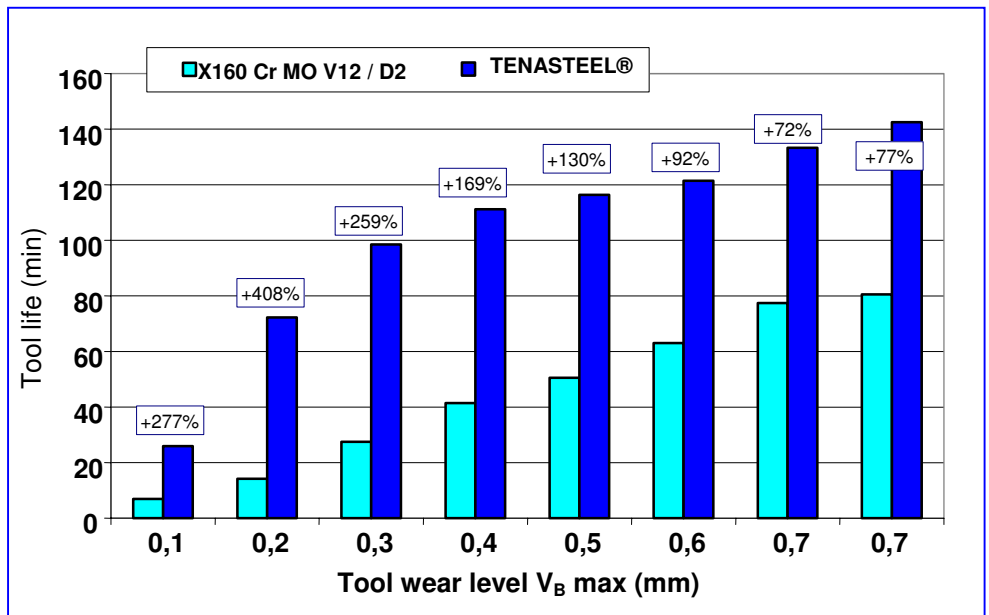
RECOMMENDED CUTTING PARAMETERS

The various machining tests carried out on TENASTEEL® result in following cutting parameters

▪ **Milling in annealed condition** (≈ 230 HB)	Carbides inserts	
	Rough milling	Fine milling
Cutting speed - Vc (m/mn)	130 /190	170 / 210
Feed – fz (mm/tooth)	0.15 / 0.4	0.1 / 0.2
Axial depth– ap (mm)	2 - 5	≤ 2

▪ **Milling in heat treated condition** (58 HRC)	Carbides inserts
Cutting speed - Vc (m/mn)	25 / 40
Feed – fz (mm/tooth)	0.2
Axial depth– ap (mm)	≤ 2

▪ **Drilling in annealed condition** (≈ 230 HB)	High tool steel drill		Insert carbide tools
	Ø < 10 mm	Ø 10/20 mm	
Cutting speed – Vc (m/min)	15	15	130 / 160
Feed per revolution – (mm/rev)	0.05 / 0.2	0.2 / 0.3	0.05 / 0.15

SUMMARY

Compared with grades X160 Cr Mo V12 / D2, TENASTEEL® allows an increase inthe tool life during machining :

- ▪ **≥ 25% in softened condition**
- ▪ **≥ 70% in hardened condition**

GENERALITIES

To obtain the mechanical properties in a given steel, with good compromise between strength and toughness, it is essential to optimize its metallurgical structure as well as the size, the distribution, the density, the homogeneity of the carbides which it contains.

This double aim can be achieved through a specially adapted composition such as in TENASTEEL® where carbon, chromium, molybdenum and titanium content, in particular, are adjusted in order to obtain excellent wear resistance and high toughness. But that is not enough. The mechanical properties of a steel with a given composition can be widely improved through heat. While influencing its structure, they will be able to increase or decrease the strength of metal and decrease its brittleness.

A heat treatment does not modify the chemical composition of metal, but has influence on :
  - its structure by control of carbide precipitation (size, distribution…) as well as the control of the nature and the proportion of the components (ferrite, austenite, martensite…)
  - The mechanical equilibrium in the metal (internal stress, expansion…).
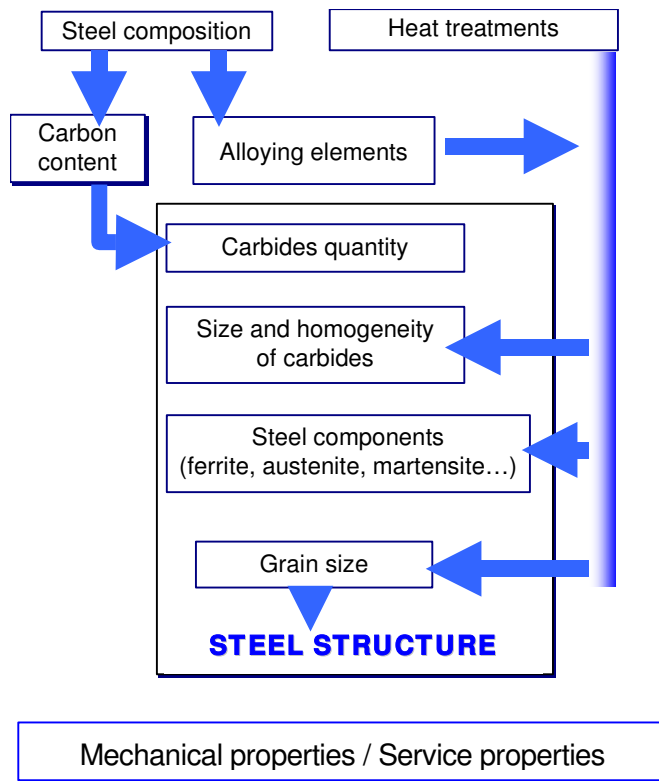

Figure 1 – Importance of the structure on the steel properties

Technically, a heat treatment is defined by a variation in temperature according to time. A thermal cycle performed on steel can be divided into three distinct stages :

▪ Heating to the desired temperature ;

▪ Time at the temperature defined according to the performed heat treatment, and depending on its final purpose (homogenization, hardening, softening, increase in ductility, internal stress reduction…).

▪ Cooling speed will fix the structure of metal in terms of components and precipitation where the several speeds of coolings can follow one another before reaching the temperature at th end of processing.

The use of heat treatment thefore requires the comprehension of the principal phenomena involved *i.e.* especially for tool steels, precipitation and dissolution of carbides, as well as the evolution of structure, their transformations and condition under which they occur.

PHASE SHIFT

Iron has the property to exist in two different crystal forms according to the temperature :
  ▪ below 910°C (*1670°F*) α iron presents a body-centered cubic mesh containing 2 iron atoms (one in the center and 8 X 1/8 at each corner of the cube ;
  ▪ Above 910°C (*1670°F*) γ iron presents a cubic mesh at centered face containing 4 iron atoms (6 X ½ in the center of the faces of the cube and 8 X 1/8 at each node).

The phase γ is denser than the phase α, Then, the allotropic transformation is accompanied by a change of volume which explains the phenomena of contraction-expansion of steel during heat treatment.
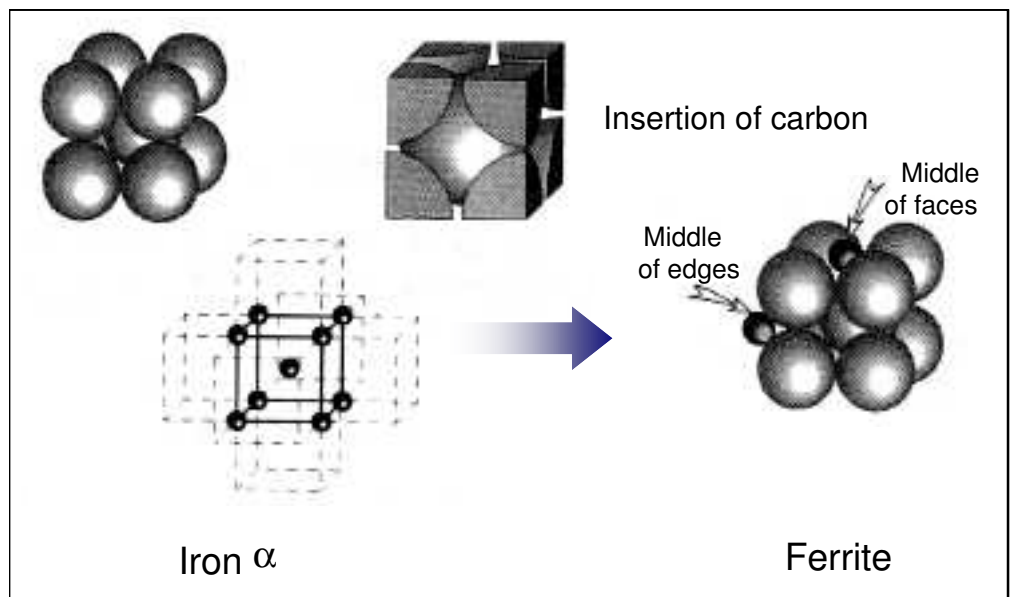

Figure 2 – Single cell of α iron of ferrite

Steel is primarily an alloy of iron and carbon in which the carbon atoms with a diameter (1,54 Å) lower than those of iron (2,5 Å) are inserted into a cell. The solid solution of insertion of carbon in α iron is called ferrite. It can contain only 0,02% of carbon at the ambient temperature and 0,045% maximum at 720°C (*1328°F*).
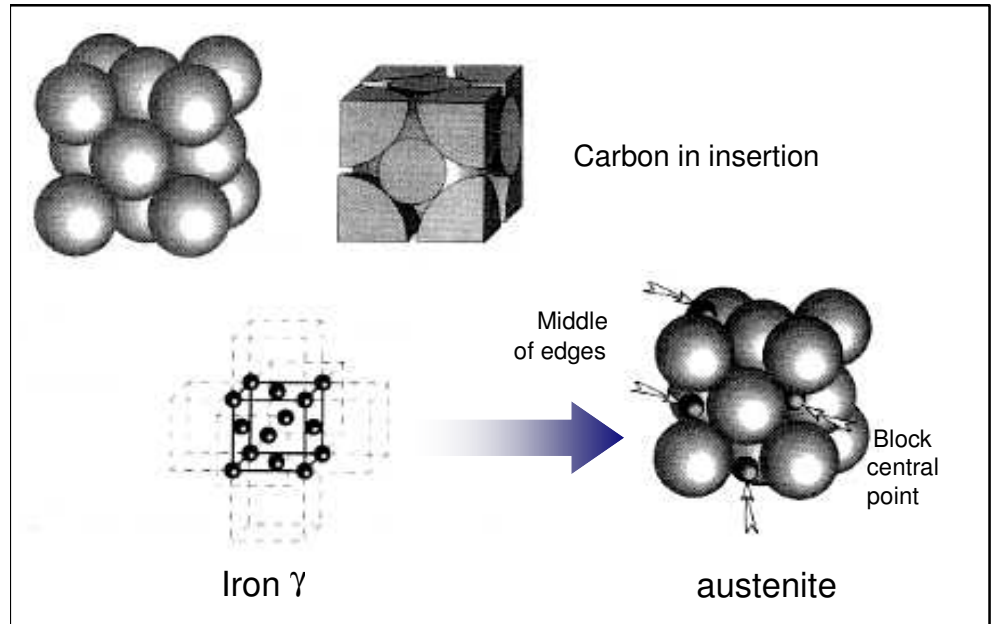

Figure 3 – Unit cell of γ iron and of austenite

The solid solution of carbon insertion into iron α is called austenite. The dissolution of carbon is more significant since it can reach 1,7%.

During the transformation of austenite during cooling, carbon will be rejected from ferrite to give cementite (iron carbides Fe_3C) or complex carbides with the alloying elements.

Austenite can dissolve more carbon than ferrite because there are more spaces in its network.

With a temperature lower than 720°C (*1328°F*), the cementite combines with ferrite to give a new structure made up of alternate lamellas of these two components. It is the pearlite which contains 0,83% of carbon. It is a relatively hard phase (200 to 250 HB), rather strong and ductile. The industrial processing leading to this pearlitic transformation is called **annealing**.

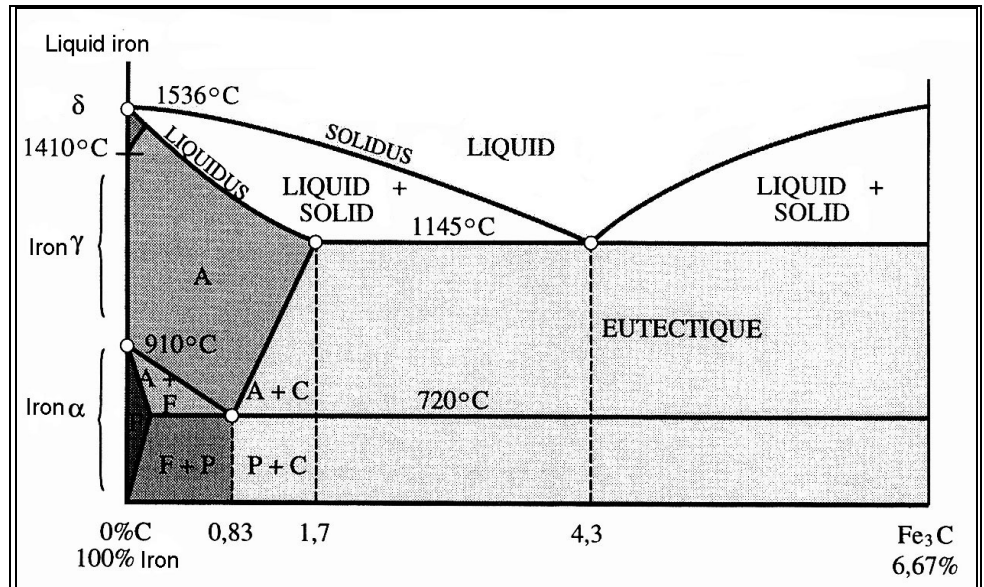The iron-carbon diagram shows the evolution of these structures during a slow cooling (or a reheating).

Figure 4 – Iron-Carbon diagram

The beginning and finishing austenite – ferrite transformation temperatures and the fields of existence of the various phases shown on the iron-carbon diagram will be modified by the presence of alloying elements in steels. The transformation temperatures will be called AC1 and AC3 if the transformation takes place during heating (ferrite $\rightarrow$ austenite) and AR1, AR3 if it occurs during cooling (austenite $\rightarrow$ ferrite).

This transformation austenite-ferrite-pearlite-cementite such as described in the iron–carbon diagram will be possible if the atoms have time to reorganize, *i.e.* during a slow cooling. On the other hand, if the time of transformation is decreased, *i.e.* that cooling is fast, a different transformation takes place at low temperatures ; austenite is transformed into martensite which is a structure supersaturated with carbon. Indeed, during the transformation $\gamma \rightarrow \alpha$, carbon could not diffuse out of the cell to form cementite. The presence of this carbon supersaturation in the ferritic cell produces significant stresses which explains the very high hardness of martensite (up to 65 HRC), but also its very high brittleness. The heat treatment which makes it possible to obtain this martensitic structure is called **hardening**. Because of its very great brittleness, martensite can never be used in this condition. A hardening is always followed by a **tempering**.

For intermediate speeds of cooling, austenite gives a mixture of pearlite and cementite : the bainite which appears as very fine needles. This component is less hard and less brittle than martensite.

The distribution of these various components, according to the speed of cooling is given by the continuous cooling transformation (CCT) diagrams. That of TENASTEEL® is shown **figure 5**.
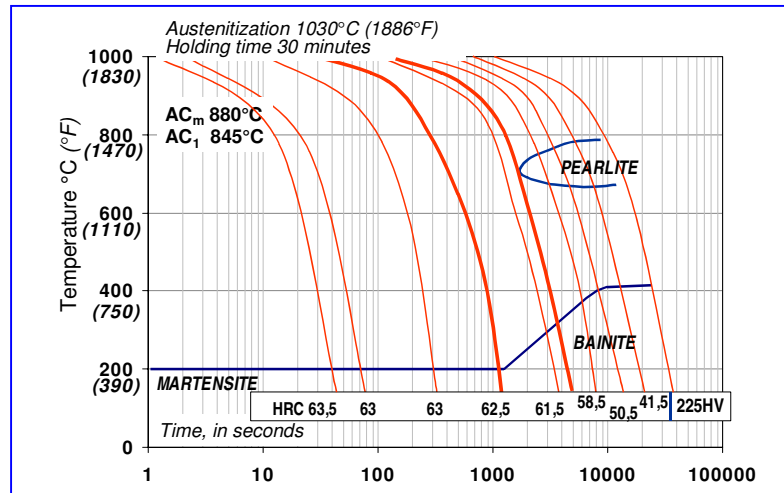
Figure 5 – CCT diagram of TENASTEEL®

FORMATION AND DISPERSION OF CARBIDES

As indicated in **figure 1**, mechanical properties of an alloyed steel depend closely on the phases present as well as the size, density, distribution and nature of carbides present in the micro-structure. This figure shows in particular the great importance of the homogeneity of distribution of carbides ; one of the main goals of heat treatment will be thus to disperse those carbides.

Indeed, during the solidification carbides precipitate preferentially in privileged zones corresponding to the grain boundaries, for example, which leads to zones with strong carbide concentration and to others with weak concentration. To reorganize the dispersion of carbides, it is necessary, initially, to dissolve them by heating the steel to high temperature. It is what occurs during the austenitizing processing. Carbides, including cementite, disappear because carbon is more easily dissolved in the γ iron structure **(figure 4).**
Nevertheless, please note that all primary carbides formed during steel solidification cannot be dissolved during austenitization.

Once dissolved, carbon will be able to precipitate during the controlled cooling of the product.

For a slow cooling, such as in the iron - carbon diagram, one will obtain ferrite with, for example, cementite formation. The carbides precipitation (iron, but also initial chromium and other alloying elements) will start at high temperature. The carbides are then very few and will share available carbon to grow bigger, especially more at high temperature where the diffusion of carbon towards carbides is fast.

In summary, **the carbides formed at high temperature (slow speed of cooling of the product) are coarse, very few and little dispersed**.

On the other hand, if the cooling is fast, the carbides will be formed later, at lower temperature. Their tendency to precipitate will be then stronger since the variation in temperature to dissolution is larger. The initial carbides will be then more numerous, but they will not have more available carbon to be shared. They will not grow bigger and will remain fine. Finer and more numerous, they will thus be better distributed, which has a big advantage. In summary**, the carbides formed at lower temperature (high cooling rate of the product) are finer, more numerous and better dispersed**. They will give an harder product.
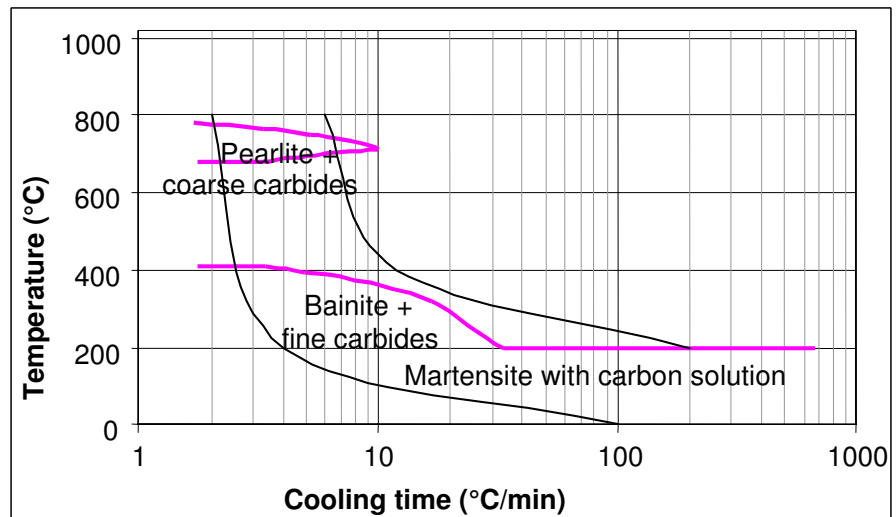

Figure 6 – *Evolution of the precipitation of carbides with the speed of cooling*

The **figure 6** shows that for very fast cooling, during hardening, part of carbon remains trapped in martensite, which will enables it to precipitate during the later tempering

VARIOUS HEAT TREATMENTS FOR TENASTEEL®

In order to facilitate its machining, TENASTEEL® is delivered in the annealed condition to give a low hardness structure. Pieces will be then hardened and tempered by the customer.

① *Soft annealing*

This heat treatment which consists in a heating at high temperature, followed by homogenization at this temperature and then slow cooling, makes it possible to bring steel in a state of physicochemical and mechanical equilibrion ; it thus causes the disappearance of the unstable states coming from heat treatments or mechanical processing performed before. It confers to the steel a low mechanical strength and a high ductility favorable to its processing. TENASTEEL® is delivered in this annealed condition.
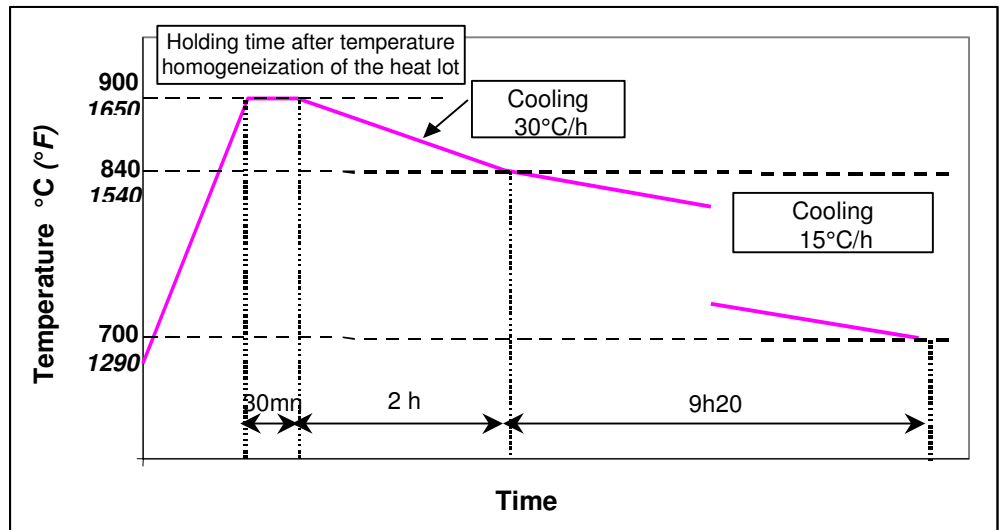
Figure 7 – Thermal cycle of annealing performed on TENASTEEL®

To obtain the required ferrito-pearlitic structure, the cooling of the product will be completely controlled. The thermal cycle of annealing ot softening practiced on the TENASTEEL® thus comprises (*figure 7*) :

- a heating to a temperature higher than AC3 (≈ 900°C) to transform the structure into austenite,

- a period of homogenization of the structure between surface and mid-thickness. The heating time is relatively short to avoid an exaggerated grain coarsening ;

- a period of slow cooling in the furnace with 30°C/h then 15°C/h until a temperature of 700°C at which all austenite is transformed into ferrite and pearlite. Then, the steel can be removed from the furnace and cooling can be completed in air since no more transformation of structure will occur.

This treatment allows to obtain a hardness of 230 HB

② ***Hardening and tempering processing***

Softened steel can be formed, but a heat treatment will be then necessary to give the final mechanical properties to the pieces. It is a quenching to harden the metal followed by tempering to eleminate its brittleness and to increase its toughness.

The process of hardening consists of

- Slow heating, to limit deformation and to Avoid cracking (due to stresses) up to a temperature just below AC1, then holding (time depending on thickness) to homogenize the temperature throughout the whole thickness. Then, re-heating up to austenitization temperature (> AC3) ;

- Holding at austenitization temperature to get an homogeneous temperature throughout the whole piece, to transform the steel into austenite and to dissolve a maximum amount of carbides previouslsy formed ;

- Cooling in an adapted cooling medium to get a martensitic structure. In order to get a martensitic transformation, it is necessary to have a cooling rate faster than critical quenching rate (of the steel) minimum speed allowing cooling without transformation into ferrite-pearlite).

The lower the critical quenching rate is, the more steel will be able to harden deeply. The hardenability of a steel depends primarily on its chemical composition. All the alloy elements, except cobalt, tend to increase hardenability. CCT diagram for TENASTEEL® (*figure 5*) shows a critical quenching rate relatively low. Its hardenability is comparable with that of steel D2.

The conditions of austenitization which controls the effective composition of austenite (more or less carbon in solution ; alloying elements present in carbides and thus inactive from the point of view of quenchability...) and the size of austenitic grains, also represent a significant parameter of the processing of hardening.

After hardening, the steel structure of is not completely martensitic, there remains a retained austenite, and carbides. The more the steel is alloyed and the higher the temperature and time of reaustenitization, the more there is retained austenite. This complex structure creates internal stresses which increase the brittleness of the steel.

To decrease the harmful effects of hardening, a new heat treatment will be perform on the pieces : the **tempering** which consists in heating at a temperature lower than AC1, to avoid modifying the crystalline iron (α) structure, then to cool quickly.

Figure 8 – Influence of heating time on the evolution of hardness during the temperature.
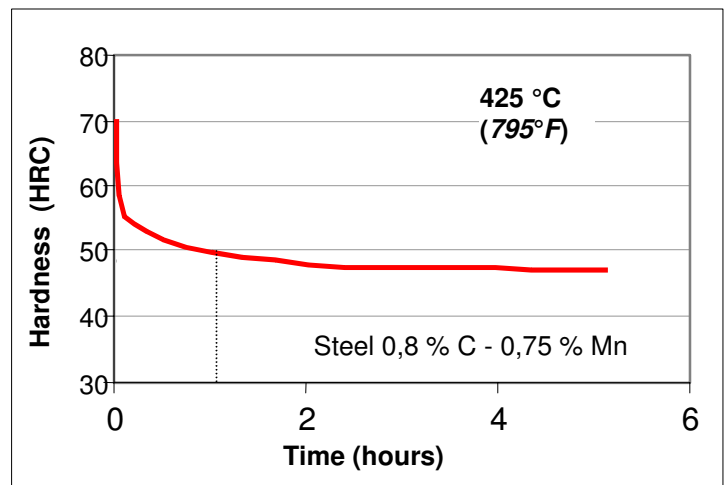
The reheating of martensite tends to bring it back into a state of balance because the carbon is rejected out of the structure and precipitates to give iron ε carbide (Fe_2C) and cementite (Fe_3C). This precipitation is accompanied by a contraction of metal and by a reduction in hardness (internal stress relaxation).

As shown in **Figure 8**, the reduction in hardness is very fast in the first minutes of the tempering (more especially as the temperature is high), it is thus not necessary to prolong it, the modifications of properties becoming then very few.

This softening due to the transformation of martensite, is attenuated by a hardening caused by the transformation of retained austenite in secondary martensite or bainite during cooling ; this reaction is accompanied by an expansion of metal. A second tempering is generally performed to transform this new martensite. Lastly, during temperings carried out at high temperature (starting from 500°C), a secondary hardening is also produced by the special carbides precipitation : vanadium and molybdenum carbides in the case of TENASTEEL®. This new hardening is also accompanied by an expansion of metal. In summary, softening with tempering results from several simultaneous phenomena (**figure 9**) :

- the softening of martensite (primary then secondary)
- the transformation of residual austenite
- the special carbide precipitation if the tempering is carried out at high temperature.
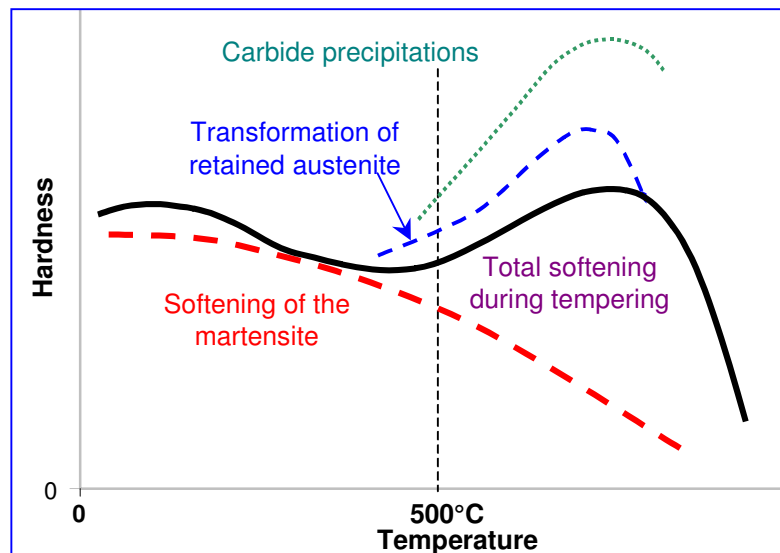

Figure 9 – Various metallurgical phenomena leading to a softening with the tempering

The thermal cycle of hardening - tempering for TENASTEEL® takes into account of these metallurgical considerations as schematized **figure 10**.
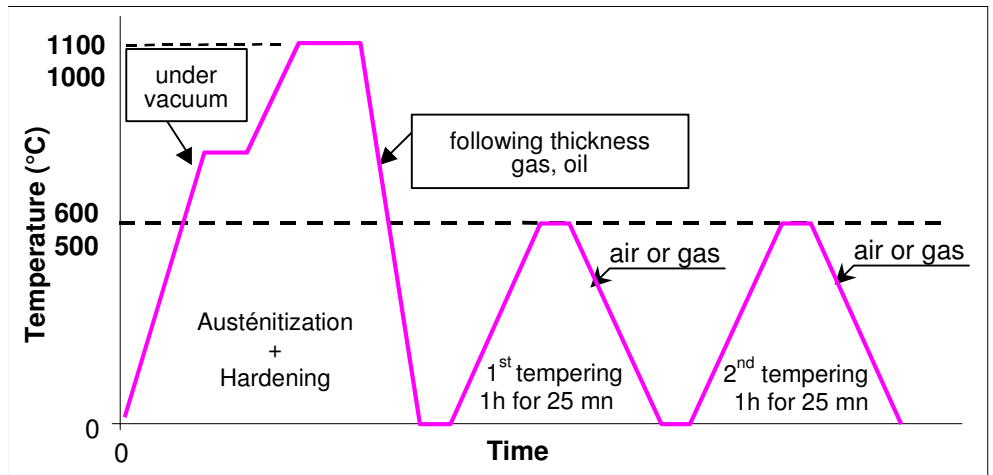.

Figure 10 – Thermal cycles of hardening and temperings performed on TENASTEEL®

Quenching parameters for TENASTEEL®

The reheating of austenitization will be performed under vacuum, or at least in a controlled atmosphere to prevent the risks of decarburization of steel. The temperature of reaustenitization can be selected between 1000 and 1100°C ; we will indicate the optimal temperature to choose according to the required properties. Heating time could be 30 minutes once the whole thickness has reached homogeneous temperature. Lastly, two temperings will be practiced between 500 and 600°C in order to benefit fully from secondary hardening ; 1 hour per 25 mm thickness of product is recommended.

The hardness evolution of TENASTEEL® after complete heat treatment is shown on *Figure 11* according to austenitizing and tempering temperatures. It should be noted that this very wide range of austenitizing temperatures makes it possible to be compatible with the temperatures usually used for many other steels (D2 in particular). This allows an optimization of furnace productivity, and thus a reduction in the costs of heat treatment, as well as a reduction in the risk of errors related to the non-observance of austenitizing temperatures.
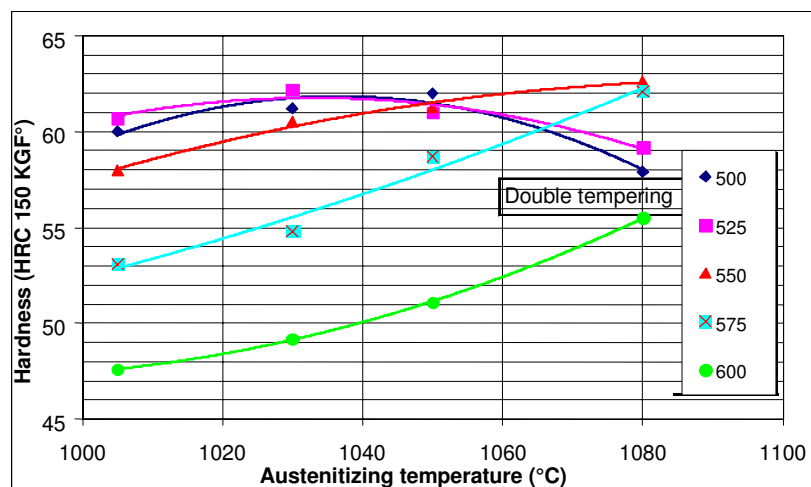

Figure 11 – Evolution of hardness of TENASTEEL® with austenitizing and tempering temperatures

Whatever the austenitizing temperature, a hardness range between 58 and 62 HRC (standard of use for this type of steel) can be obtained if TENASTEEL® undergoes two temperings between 500/550°C (*930/1020°F*) to 575°C (*1065°F*). A double tempering at 600°C (*1110*°F) will have to be reserved for certain very special applications for which a maximum softening is necessary, if an extremely high impact strength is sought. Although an austenitization between 1000 and 1100°C (*1830/2010°F*) leads to a good hardness in TENASTEEL®, the best properties will be obtained after reheating around 1030 - 1050°C (*1885-1920°F*). Indeed, **Figure 12** shows that the toughness of metal is maximized in this range of temperature.
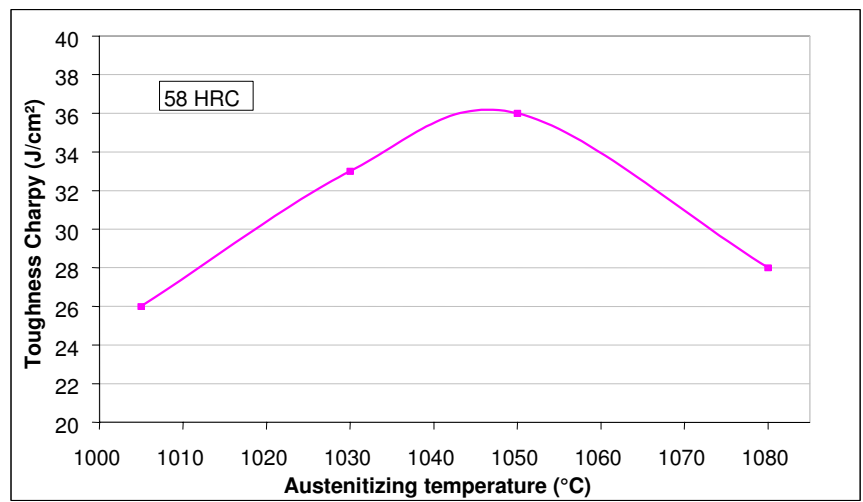

Figure 12 – Effect of austenitizing temperature on the toughness of TENASTEEL®

However, if the austenitizing temperature is too low, a large part of chromium carbides will not be dissolved. They will remain coarse and will not increase hardness and wear resistance of steel. In addition, for the highest reheating temperatures, the hardening obtained by the refinement of carbides is counterbalanced by softening due to the increasing in retained austenite rate after hardening. A third tempering should then be necessary to completely destabilize this retained austenite.

Concerning quenching, CCT diagram (**figure 5**) shows that V_2 cooling speed below which austenite is transformed into pearlite is 10°C/min.
V_1, critical cooling speed from which austenite is transformed only into martensite, is about 33°C/h
Those cooling speeds can be obtained by air quenching for thicknesses up to 25mm. For thicknesses over 25mm, quenching shall be done by air.

SUMMARY

Austenitization and quenching can be done in following conditions :
- **Austenitization 1020/1050°C (*1870-1920°F*) ;**
- **Holding time 1 hour per 25 mm of thickness**
- **Air quenching for t ≤ 25mm**
  Oil quenching for t > 25 mm

Tempering conditions for TENASTEEL®

Number and temperature of temperings used to soften martensitic structure after quenching will allow TENASTEEL® to obtain final mechanical characteristics and final service properties.

The softening curves of TENASTEEL® are compared with those of the D2 **Figure 13** for an austenitizing temperature of 1030°C (_1885°F_) and **Figure 14** after reheating at 1050°C (_1920°F_).
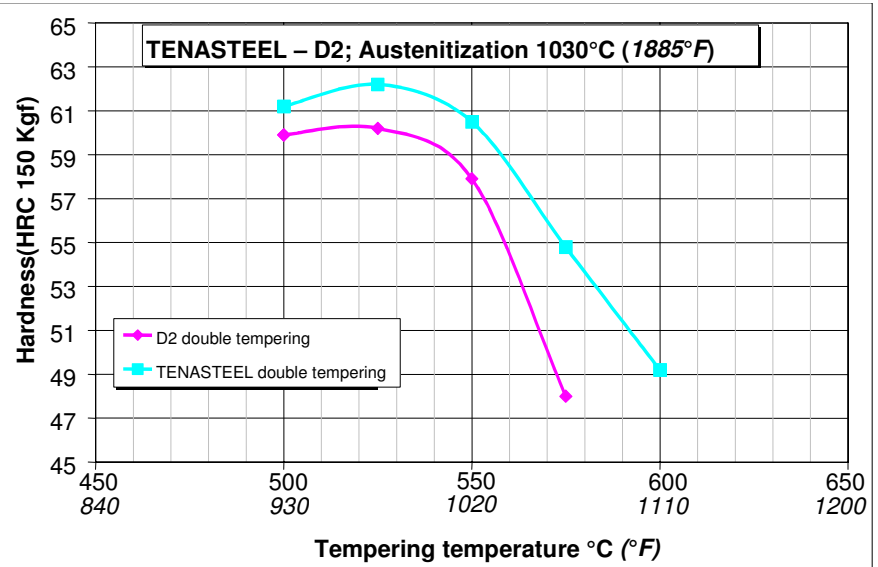

Figure 13 – Softening curve of TENASTEEL®, compared with that of the D2
Austenitizing temperature : 1030°C (_1885°F_)
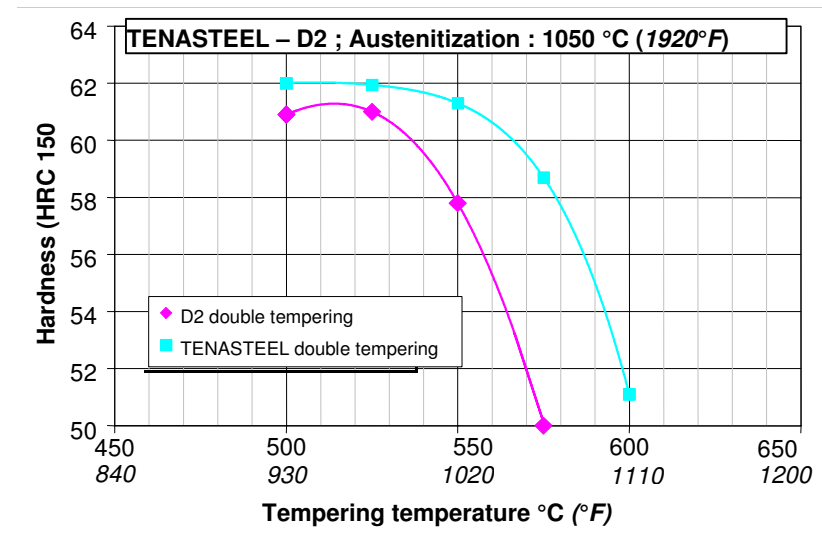

Figure 14 – Softening curve of TENASTEEL® compared with that of the D2
Austenitizing temperature : 1050°C _(1920°F)_

These softening curves of TENASTEEL® make it possible to draw some interesting conclusions :

- TENASTEEL® and D2 grades are treated in the same ranges of temperatures,

- For an identical tempering temperature, TENASTEEL® achieves a greater hardness than D2,

- Finally, TENASTEEL® makes it possible to obtain high hardnesses (> 60 HRC) after temperings at high temperature (500 - 550°C).

  This is advantageous when treating which requires relatively long holding time at high temperatures for nitriding (gas, bath of salts, ionic...) or PVD, for example. These softening curves show that for processing performed between 550 and 575°C TENASTEEL® is able to maintain a hardness of the matrix higher than 60 HRC, whereas the Z160CDV12 sees its hardness reduced to 50 - 58 HRC in this temperature range. More precise details on the aptitude for surface treatment of TENASTEEL® will be given later.
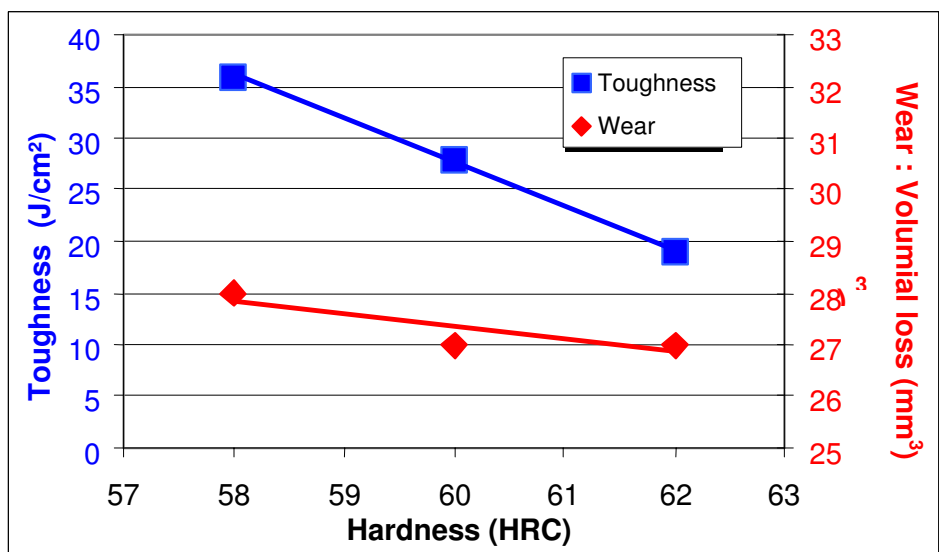

Figure 15 – Evolution of mechanical properties of TENASTEEL®
following hardeness obtained after heat treatment

The evolution of mechanical characteristics obtained after heat treatment is shown on **Figure 15**. The toughness of TENASTEEL® strongly grows with the reduction in the hardness of steel, whereas its wear resistance increases slightly with hardness. The best compromise, for a standard application, is obtained after two temperings between 525 and 575 °C ; the tempering time is equal to 1 hour per 25 mm thickness of the product.

Lastly, due to the broad ranges of temperatures available for austenitization as well as tempering of TENASTEEL®, it is easy to adapt the heat treatment to achieve the required final properties. **Figure 16** summarizes optimal processing for current applications.

Of course, additional heat treatments are possible for special applications. For example a hardness of 50 - 55 HRC leading to a maximum toughness can be obtained by a double tempering at 600°C (*1110*°F). For other specific application, **figure 15** gives the hardness according to the mechanical properties wanted ; then see **figures 13 and 14** to slect the best heat treatment.
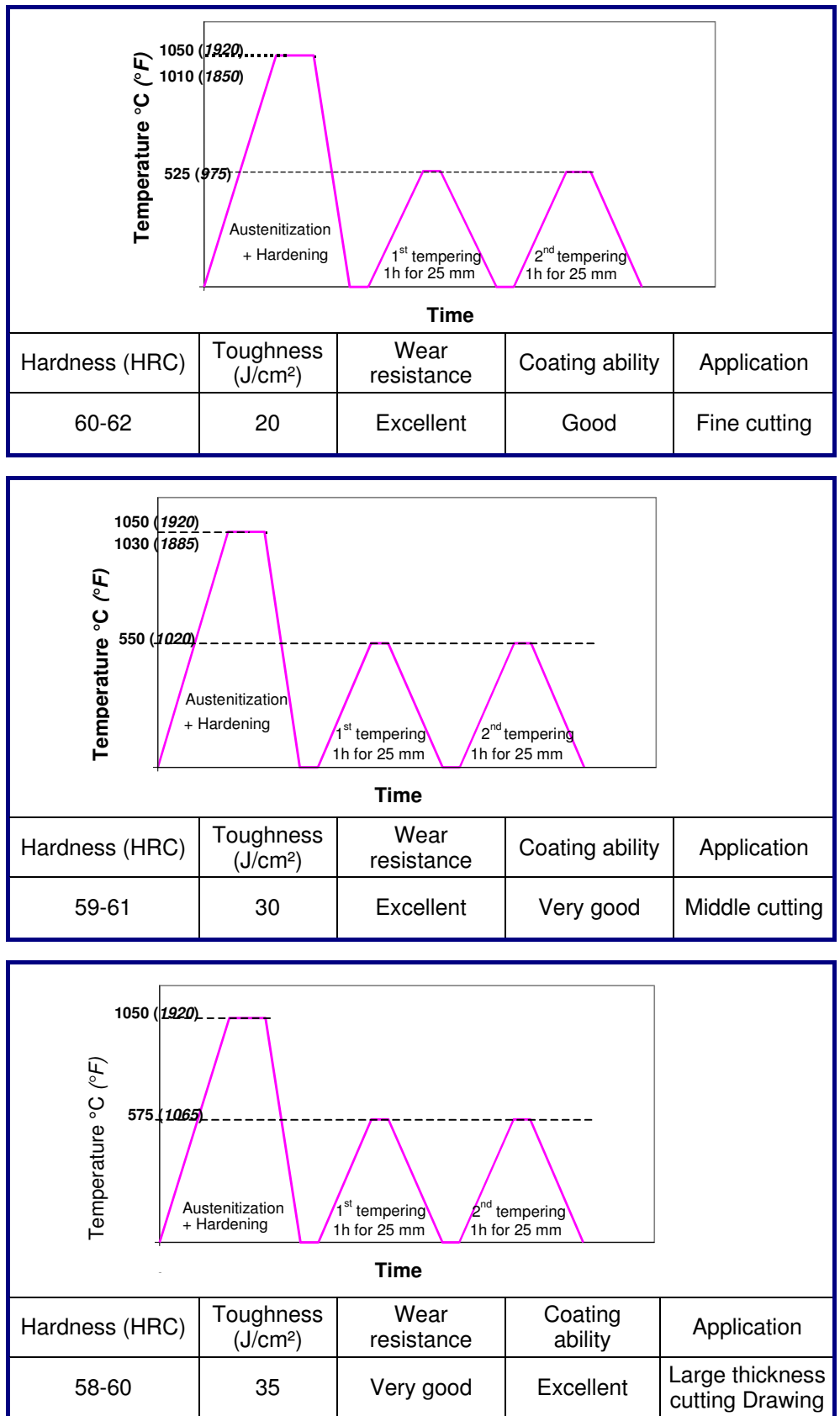
Chart 1

Temperature °C (°F)

1050 (*1920*)
1010 (*1850*)

525 (*975*)

Austenitization + Hardening   1st tempering 1h for 25 mm   2nd tempering 1h for 25 mm

Time

Hardness (HRC)	Toughness (J/cm²)	Wear resistance	Coating ability	Application
60-62	20	Excellent	Good	Fine cutting

Chart 2

Temperature °C (°F)

1050 (*1920*)
1030 (*1885*)

550 (*1020*)

Austenitization + Hardening   1st tempering 1h for 25 mm   2nd tempering 1h for 25 mm

Time

Hardness (HRC)	Toughness (J/cm²)	Wear resistance	Coating ability	Application
59-61	30	Excellent	Very good	Middle cutting

Chart 3

Temperature °C (°F)

1050 (*1920*)

575 (*1065*)

Austenitization + Hardening   1st tempering 1h for 25 mm   2nd tempering 1h for 25 mm

Time

Hardness (HRC)	Toughness (J/cm²)	Wear resistance	Coating ability	Application
58-60	35	Very good	Excellent	Large thickness cutting Drawing

Figure 16 – Examples of heat treatments recommended for TENASTEEL®

**CRYOGENIC
TREATMENT**

For most tool steels, the temperature at the end of martensitic transformation is lower than ambient temperature. Consequently, during a traditional hardening finished at room temperature, retained austenite remains, which transforms partly during temperings, if conducted at high temperature. Unless the number of the temperings are increased (4 or 5), a small percentage of retained austenite remains always in metal.

Figure 17 shows that it is necessary to perform a double tempering at least at 550°C to reduce the residual austenite level less than 1%, after austenitization at 1050°C.
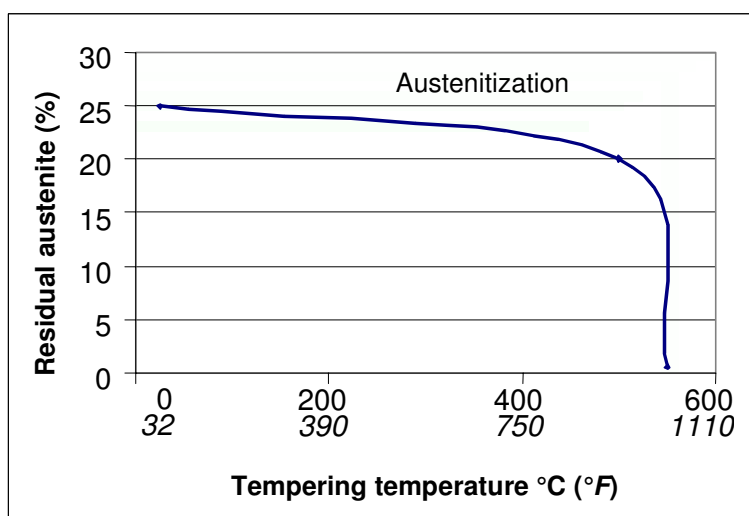

Figure 17 - **Evolution of austenite rate, as a function of double tempering temperature.**

This small quantity of retained austenite will then transform very slowly at room temperature and will lead to a dimensional unstability of pieces after heat treatment.

To increase the dimensional stability of pieces, it is interesting to remove this austenite through cryogenic treatment to pass below the temperature of end of martensitic transformation. Various precautions must be taken :

- Cooling must be carried out immediatly after hardening, maintaining the room temperature would stabilize austenite.

- The optimal temperature of refrigeration is located between -60 and -100 °C (*-110 and -150°F*). At these temperatures, martensitic transformation is not instantaneous as it is above 0°C (*32*°F).   A certain holding time of maintenance is thus necessary : typically 2 to 3 hours.

- Reheating after refrigeration must be slow to allow transformation of the austenite not transformed during the holding at low temperature. Slow heating will also reduce internal stresses and risk of cracking (structure 100% martensitic, so very brittle).

The processing recommended for TENASTEEL® takes into account these recommendations ; it is represented (**figure 18**) here after :
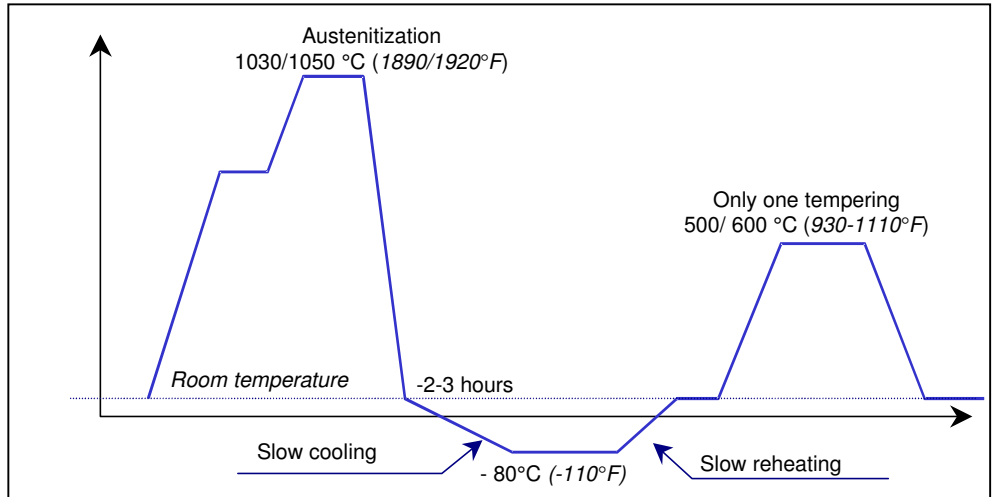

Figure 18 – Cryogenic processing to apply to the TENASTEEL®

The transformation of the major part of residual austenite leads to an additional increase in hardness after the only tempering necessary. **Figure 19** here after shows this higher hardness when metal underwent a cryogenic treatment. In this case, hardnesses of 64 HRC can be obtained after a tempering at 500 °C (930°F), whether steel was austenitized at 1030 or 1050 °C (*1890 or 1920°F*).
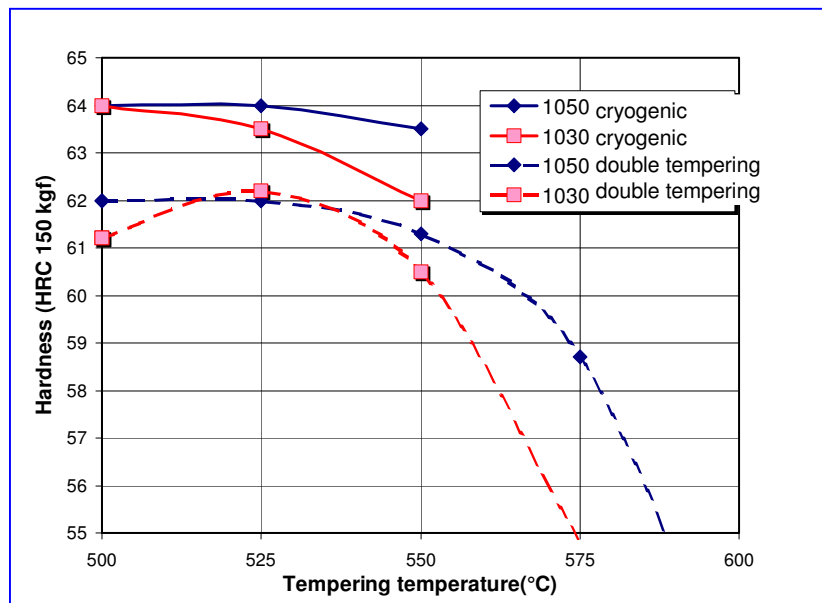

Figure 19 – Evolution of hardness measured on TENASTEEL® after heat treatment

TENASTEEL® cutting parameters will be similar to those of X160 Cr Mo V12 / D2.

Nevertheless TENASTEEL®

- Avoids many disadvantages through a better uniformity of its structure and the largest smoothness of its carbides.
- Reduces greater risks of cracking.

GENERALITIES

E.D.M. wire cutting is a very interesting process, which allows

- To cut the tool in the heat treated condition,
- To reduce stresses introduced in the material,
- To obtain very precise dimensions and very complex shapes which are not compatible with traditional machining.

PRINCIPLE

E.DM. wire cutting is based upon the erosive effect of electric sparks produced between a moving conductor wire and the workpiece which is used as cathode, separated from one another by a dielectric medium.

Under the effect of the electric discharge, the surface temperature can reach 8000 to 12000°C. At these high temperatures, the morphology of the extreme surface is substantially modified as follows :

1. Melted and re-deposited metal, zone made up of microscopic clusters of re--solidified metal on the underlying white layer ;

2. Very hard white layer consisting of remelted and recarburized metal that is then cooled very quickly (its structure does not react to the usual metallographic reagent, hence its name).

3. Heat affected zone.
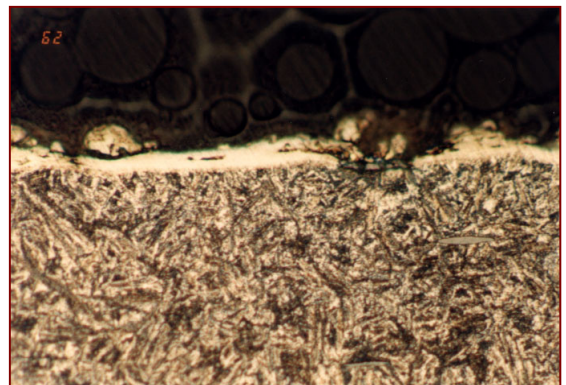
The thickness of the surface layers affected by EDM varies considerably and may range from a few micrometers to a few hundredths of millimeters, depending on working conditions.

In certain circumstances, cracks may appear. Generally, the surface properties of the material are completely modified in terms of structure, hardness or internal stresses.

Note that a number of parameters play a decisive role in the success of the EDM process. Although a poor quality material raises systematic difficulties, it is clear that a perfectly homogeneous steel will perform badly under EDM if certain rules are not respected.
For example, the more energy is released at the surface of the piece, the more material is removed. However, if a certain limit is exceeded, the surface quality of the piece will be degraded.
Accordingly two parameters appear to be essential:

- The quality of the material to be eroded: degree of homogeneity, density of inclusions, etc…

- The EDM parameters: current density, pulse on / pulse of / flushing time, etc…

① *The E.D.M. process*

In this section, we shall review certain precautions that are necessary to ensure the success of the EDM operation. For this purpose, we shall use the results of research carried out by professionals.
To begin with, we shall list the different parameters involved in EDM by wire or by immersion :

- The choice of electrode material,

- The choice of dielectric,

- Electric power (current or voltage),

- Discharge time : duration of the spark,

- Waiting time : time between 2 sparks,

- Setting of the wire/piece distance

The choice of these parameters will have a decisive effect in the final quality of the machined part in terms of meeting geometrical dimensions, surface roughness and thickness of the white layer.

To obtain a good surface finish for example, the current must be reduced. If the duration of the discharge is increased at the same time, the white, thermally affected zones must be expected to be thicker.

Generally speaking, the operators have the experience, which allows obtaining good surface quality as a function of the parameters of electric pulse intensity and duration.

② *The material*

Advantages of TENASTEEL®

Although it is not appropriate to increase the speed of EDM with TENASTEEL®, consideration must nonetheless be given to the time savings and fewer contingencies resulting from the uniformity of structure and low inclusion density of this steel (comparing with X160 Cr Mo V12 / D2), that eliminate many of the complications involved.

Also the lower carbon content of TENASTEEL® :

- Reduces the risks of cracking caused by the thermal effects of EDM (for the same reasons as with welding) ;

- Reduces the depth of the zones affected by EDM simplifying their subsequent removal by polishing ;

- Improves the surface condition of the cutting (low heterogeneities due to carbide segregation).

③ *Damages, due to wire cutting for tool steels*

- Heat affected zone / Remelted zone
  → hard spots and micro-cracks risks

- Stress relaxation

  → deformation

  → Cracks on sensitive zones, like sudden modification of section, inside angles, etc…

④ *Solutions*

■ *Limit internal stresses before cutting*

  ➢ Adapted quenching conditions to the thickness of the tool ; no excessive cooling ;

  ➢ Low heating before quenching, with intermediate stage at about 700/800°C to homogenize the temperature before transformation point.

  ➢ Necessity for a double tempering at the highest possible temperature, compatible with the hardness requested .

  ➢ In case of wide section pieces, drilling holes to discharge internal stresses may be done. This allows to cut internal draws by wire cutting, later, without any problem.

3. Lines of wire cutting

2. Lines to join holes

1. Drilling
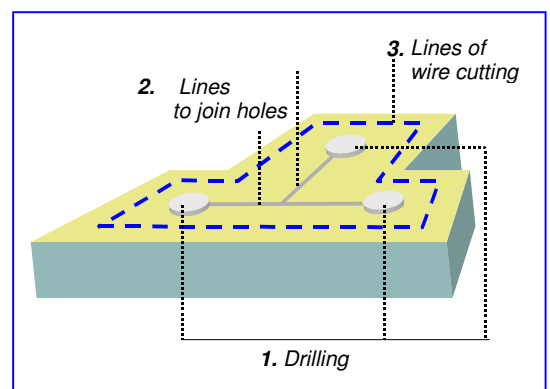
■ *After cutting*

➢ If cutting before heating, polish E.DM. surfaces to remove hardened white layer created by wire cutting.

➢ If cutting after heating (recommended) :
  ▪ Proceed with finishing parameters,

  ▪ Polish E.D.M. surfaces and/or make a stress relieving heat treatment immediately at a temperature 15 to 20°C lower than tempering temperature.

SUMMARY

▪ **Wire cutting parameters are the same for TENASTEEL® as Z160 CDV12.**

▪ **It is important to remove the white layer by polishing to avoid in-service cracking risks.**

▪ **The TENASTEEL® thin structure allows improved cutting surface conditions and reduces cracking risks.**

GENERALITIES

The polishing of cold work tools, forming, cutting, meets multiple needs :

- To guarantee a fine surface quality before surface coating (PVD, CVD) in order to improve quality of the deposits and to help their adhesion with the support.

- To improve the coefficient of friction

  → to improve the sliding of materials in forming tools,
  → to reduce adhesion wear in the cutting of soft materials (copper, aluminum, austenitic stainless steel...)

- To eliminate the E.D.M. white layer which is particularly brittle and sensitive to cracking by mechanical fatigue.

The surface quality obtained after polishing thus has a purely functional aspect, because it will influence directly the performances of the tools. The evaluation of the result will thus be based on a measurable criterion, roughness, the visual aspect having no justification for this type of application.

The quality of polish obtained depends of course on the procedure of polishing, but it is also strongly influenced by the smoothness and the micro-structural homogeneity of steel. Owing to its fine structure, and compared to a X160 Cr Mo V12 / D2, TENASTEEL® ensures
- faster polishing,
- better surface quality.

The in-service output of the tools will thus be improved, mainly in the cases of adhesion wear.

FACTORS OF SUCCESS

Among the various factors influencing the quality of the polish, 3 following points have to be noted:

- The metallurgical quality of steel,
- The types and conditions of mechanical machining used in the manufacturing of the piece to be polished,
- The procedure of polishing.

The surface quality obtained with polishing, therefore the performance of the tool will depend on the optimization of these 3 factors.

■ *Metallurgical quality*

A good surface quality depends on the structure of the steel.

In most of cold work tool steels, strongly carbon alloyed, the presence of primary carbides formed during the solidification of steel can be observed.
The number and the size of these carbides are directly proportional to the percentage of carbon in the steel.

If carbides may have a positive action in the wear resistance, they generate a certain number of disadvantages:

- Very hard particles (> 1500 Hv) in a softer matrix, they are easily torn off during polishing and cause small cavities and scratches on polished surfaces (increased in time of polishing).
  Tearing off will be especially easier, scratches will be particularly large, as carbides are big.

  Thanks to its lower carbon content, carbides of TENASTEEL® are fine and ensure a fast and reliable polishing.

- Strongly alloyed steels frequently present at mid thickness carbide concentration in the form of veins known as "segregated zones". In these zones carbides are coarser. Polished surfaces crossed by these veins will thus present at this place surface irregularities with a roughness more significant than other parts of the matrix and even geometrical defects, like "waves", resulting from a higher local hardness.

  TENASTEEL® will be again less sensitive to this type of defect, compared with X160 Cr Mo V12 / D2, thanks to its lower carbon content.

- The presence of coarse carbides, mainly in segregated zones, can also lead sometimes to discover micro-porosities during fine polishing. These small cavities come from dislocations produced between carbides and the matrix at the time of the operations of forging or rolling.

TENASTEEL®, which has a lower carbon content and consequently finer carbides than X160 Cr Mo V12 / D2, thus offers a better aptitude for the polishing which results in :
- reduction of polishing times,
- lower roughness (for an abrasive of equivalent granulometry),
- more homogeneous surface quality through the thickness,
- less risk of micro-porosity at mid thickness.

It should be noted that other parameters influence the surface quality of the polished tools :
- the cleanliness of the steel : the surface quality improves when the number and the size of inclusions decreases,
- the hardness of steel : a higher hardness increases the time of polishing but allows one to obtain a better surface quality.

■ *Types and conditions of machining*

Mechanical machining under severe conditions can sometimes cause structural changes to the surface. However further thermal treatments to regenerate the structure cause no polishing. In fact, only roughness aftachievement of a good polish but it will considerably increase the time of polishing.

Cutting with the wire (E.D.M. carried out after heat treatment) will have a more significant influence. This operation creates a surface layer known as "white layer", very hard, very brittle which can be affected with micro cracks. This layer must imperatively be removed by grinding and/or polishing. The use of moderate parameters of E.D.M. will anable to obtain a thin white layer, limiting polishing times.

■ *Techniques of grinding and polishing*

Roughness obtained will not be optimum ; the aim of **grinding** is to optimize characteristics of friction of the tools.

During grinding, it is advisable to avoid an excessive heating of the which can deteriorate the structure of steel.
Therefore, grinding pressure should be limited, while sprinkling the pieces.
TENASTEEL® should be ground with aluminum oxide or boron nitride grinding stones when grinding in the heat treated condition.

Polishing can be manual or automatic. When possible, machine polishing is preferred.

2 main stages:

- Pre-polishing, which consists in successively eliminating the traces from polishing with a paper of given grit, by new traces with the paper of the next and decreasing grit. With each change of grit, the piece is washed then generally dried with compressed air. Moreover, with each change of grit, polishing must undergo a 90° rotation so that the new scratches from polishing are perpendicular to the previous scratches.

  Papers used are of decreasing grit from the type 100 - 180 - 320 - 600 then 1000 under water.

- Fine polishing uses felt discs impregnated with diamond paste of granulometry 9 µm to 1 µm. The piece is then degreased with ether, alcohol, and is dried immediately to avoid any risk of corrosion on the polished face.

For the stages of pre-polishing, alumina with various grit remains the abrasive most employed. For fine polishing, the abrasive used will be a diamond base.

Excessive operator or machine polishing pressure, can cause a significant work hardening, even a localized heating. The more one will advance towards the finishing stages, the more the pressure applied will have to be low.

Concerning polishing time, the general rule specifies that, when the size of abrasive grit has led to the elimination of all the scratches left by the previous grit, it is advisable to go at the next stage. It is commonly allowed that there is an optimum time of polishing beyond which the state of polish is deteriorated.
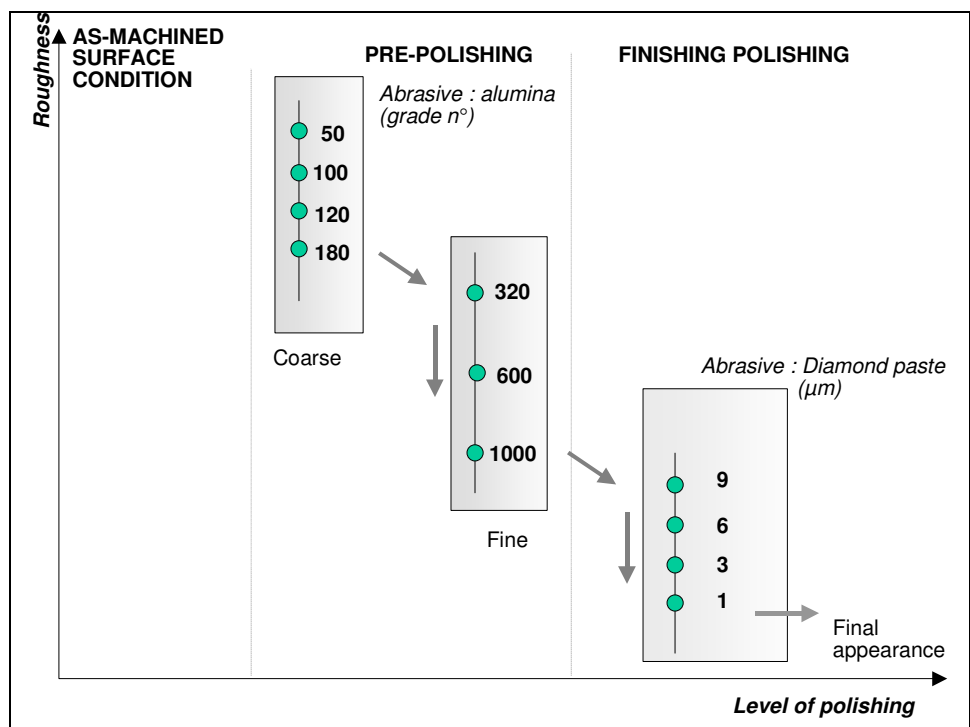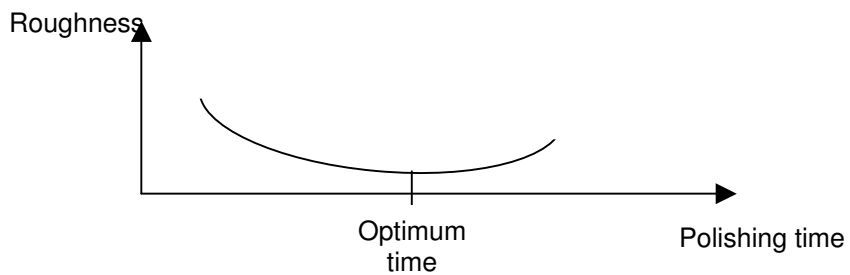
SUMMARY

- ▪ **TENASTEEL® polishing methods are the same AS for X160 Cr Mo V12 / D2.**
- ▪ **Fine structure of TENASTEEL® enables a faster polishing and a better surface quality.**

In order to increase their resistance to seizing and to minimize the friction in service, tool steels are more and more frequently surface treated by nitriding or covered by metal deposits. This surface treatment also makes it possible to increase the surface hardness of pieces and to increase the tool life subjected to abrasive and/or adhesive wear.

THERMOCHEMICAL SURFACE TREATMENT: NITRIDING

Nitriding is a thermochemical process of hard facing by atomic nitrogen diffusion on the surface or the pieces treated beforehand by hardening and tempering. The insertion of nitrogen atoms and the nitride formation with steel alloying elements, induces a surface hardening (750 to 1400 HV) bringing the required properties :

- Improvement of resistance to wear and seizing of materials ;
- Increasing the stress limit of material thanks to the compressive stresses created by the processing ;
- Maintain of metallurgical structures of the material and thus of its internal mechanical characteristics if the tempering has been carried out at a temperature higher than that of the surface treatment.

Moreover, as this process does not require any hardening after diffusion, deformation of pieces is limited. A systematic expansion, caused by the nitrogen introduction in the crystal network of the material is nevertheless noted. A change of the position of machining allowances is thus to be required.

■ *General principle*

In contact with the centered cubic crystallographic structure steel heated beyond 450°C, the very small nitrogen ions penetrate easily in the lattices (☐) that they saturate quickly by occupying the vacant sites. Then, they form nitrides while combining with the iron atoms of surface (☐) to constitute a layer of very hard combination. Then, nitrogen penetrates inside the steel to give a layer of diffusion which thickness will be as a function of the temperature and the time of treatment (☐).
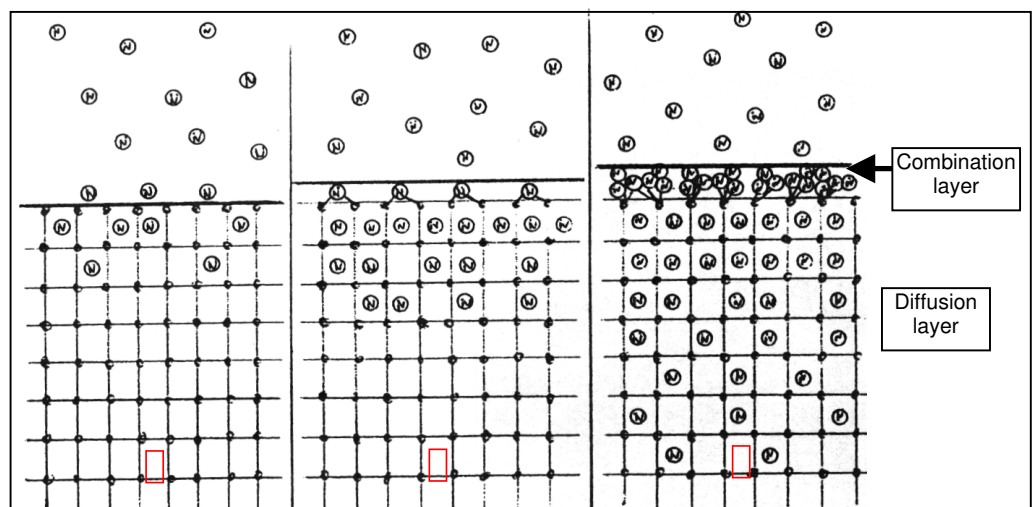

Figure 1 – Mechanism of nitriding of a steel

Figure 1 schematizes the mechanism of diffusion of nitrogen in steel, and *Figure 2* shows the various layers formed on the TENASTEEL® nitrided by gas process.
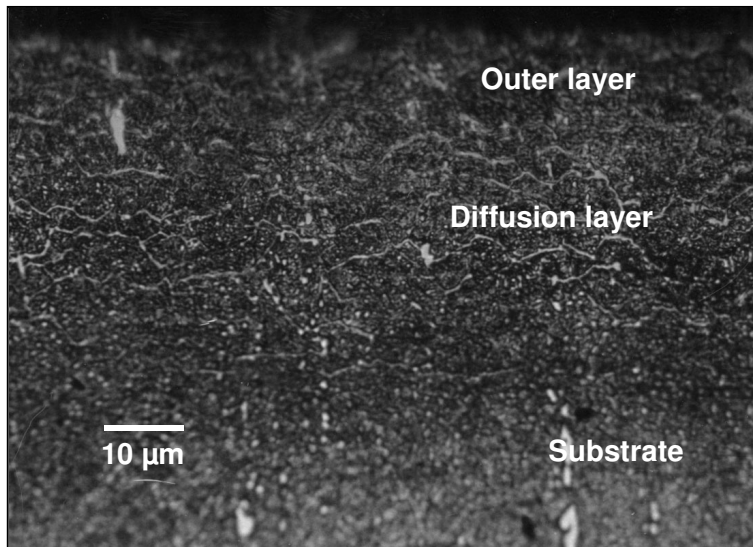

Figure 2 – Micrography of a sample of TENASTEEL® after gas nitriding

While penetrating in the lattice, the nitrogen pushes back the carbon of the steel, which makes it possible to highlight the layer of diffusion. The thickness of the layer of diffusion can also be estimated starting from a hardness reading from surface towards the middle of the steel. *Figure 3* shows that this thickness is very difficult to be exactly measured.
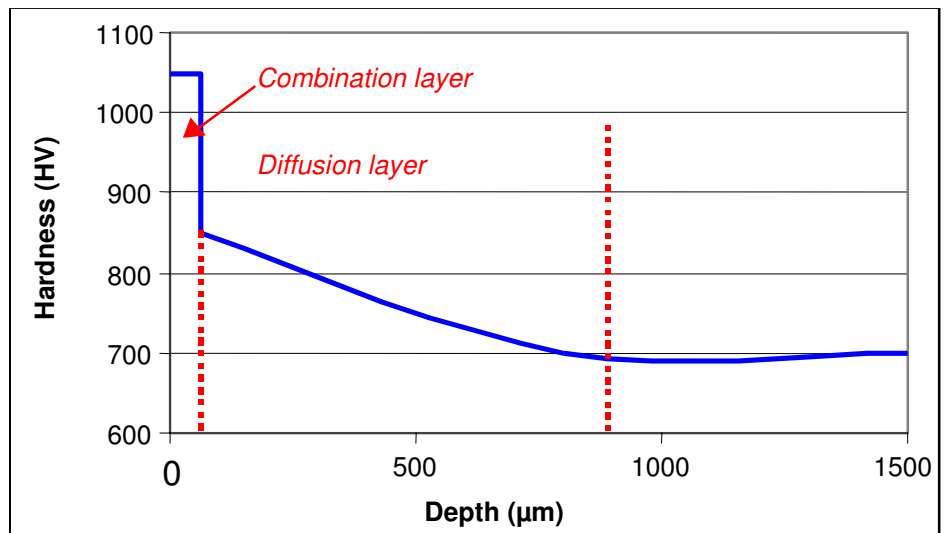
Figure 3 – Micro-hardness readings starting from the surface of a nitrided layer

The outer layer is made of very hard iron nitrides. It improves sliding properties and wear / galling resistance. The underlying diffusion layer ensures a good fatigue behaviour and contributes to wear resistance also.

The hardness of the nitrided layer is due to residual stresses which are induced in the structure (**figure 4**) by insertion of the nitrogen atoms and formation of nitrides which can take two crystal forms :

- **Hexagonal for the phase ε**
  (cell parameters a = 5,53 Å, b = 4,83 Å et c = 4,42 Å) for iron nitride $Fe_{2,3}N$

- **Cubic for the phase γ**
  (with faces centered with a cell parameter of 3,79 Å) for the Fe_4N nitride.
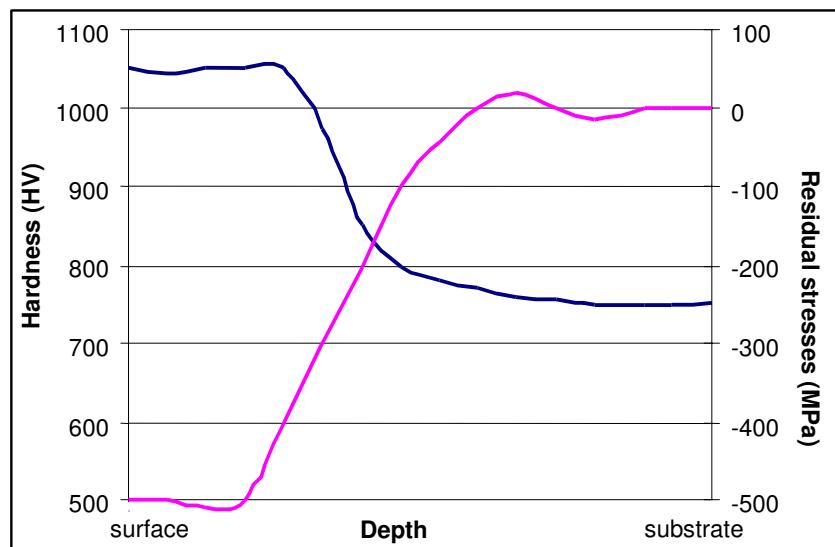
Figure 4 – Influence of residual stresses in the nitrided layer on the evolution of its hardness

Characteristics and thicknesses of these various components of thenitrided layer are a function of the grade, the temperature, the time and the nature of the treatment, since nitriding can be obtained
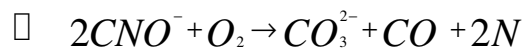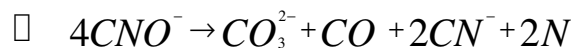
- in salt baths,
- by gas process,
- by ionic pelting.

The table hereafter summarizes some advantages and disadvantages of the various techniques of nitriding.

Nitriding	Advantages	Disavantadges
Salt baths	▪ Cheap ▪ All sizes and shapes of pieces ▪ Outer layer : porous then compact → Pores can be used as lubricant holders → improvement in the coefficient of friction.	▪ Treatment and elimination of salts (environment) ▪ Process less and less used ▪ Surface : increased roughness ▪ Possible grinding to eliminate the fragile outer layer
Gaseous	▪ Deep treatment hard and compact (Outer layer) ▪ Easy process ▪ Inexpensive treatment ▪ Treatment of large pieces	▪ Low flexibility in the process ▪ Toxic gas ▪ Grinding may be necessary to eliminate the brittle combination layer
Ionic	▪ Flexible process ▪ Possibility of treating at low temperature (starting from 450°C – *840°F*) ▪ No further grinding ▪ Fast process, not pollutant and of great cleanliness ▪ Toughness of nitrided layers ▪ Unchanged surface morphology	▪ Expensive treatment ▪ Treatment of lot of pieces of close geometry ▪ Difficulty in treating small borings

Some aspects of different nitriding methods

■ ***Salt bath nitriding***

In this process, the nitrogen atoms are obtained by the decomposition and the oxidation of cyanates present in the baths where the pieces are immersed according to equations ⬚ and ⬚ :

$$\text{⬚} \quad 4CNO^- \rightarrow CO_3^{2-} + CO + 2CN^- + 2N$$
$$\text{⬚} \quad 2CNO^- + O_2 \rightarrow CO_3^{2-} + CO + 2N$$

The formed cyanides (CN⁻) are eliminated by sulphides in the processes Sursulf and Sulfinuz and by regenerating salts close to urea in the case of the Tenifer process.

Thanks to the strong nitriding potential of salt baths, this process makes it possible to obtain layers of nitriding with a relatively short processing time. Typically, 30 minutes to two hours of Tenifer in our tests conducted on TENASTEEL®. **Figure 5** hereafter shows the results obtained under these conditions.
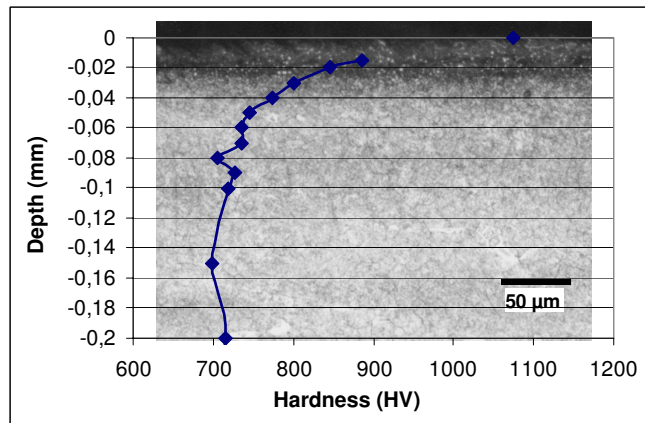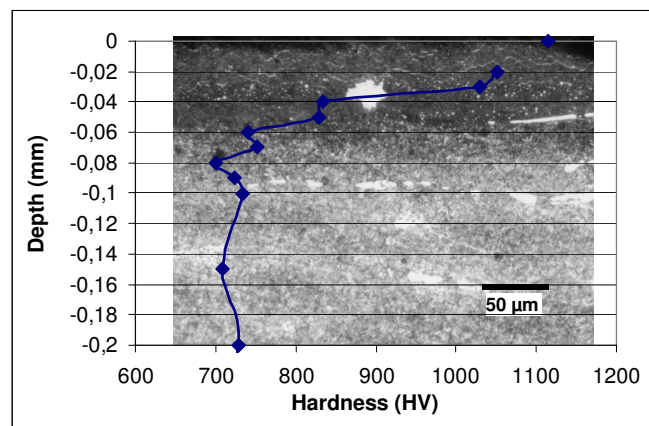
Figure 5

Morphology and characteristic of nitrided layers obtained through Tenifer processing (30 minutes and 2 hours) on TENASTEEL®.

After 30 minutes of treatment at 570 °C (*1060°F*) the combination layer, 15 to 20 µm, has a hardness of 1050 HV. The diffusion layer can be estimated at 20 µm. If the processing is prolonged up to 2 hours, the outer and diffusion layers can reach respectively 30 and 30 to 35 µm. The surface hardness increases up to 1115 HV.

These thicknesses can be estimated through micrographies and hardness readings represented in **figure 5**.

Lastly, **figure 6** hereafter shows the evolution of the hardness of the matrix of TENASTEEL® under the nitrided layer. After 30 minutes of TENIFER process, an average of 675 MV corresponding to 59 HRC is preserved in the core of the piece. On the other hand, a slight drop of hardness is observed after 2 hours of process in salt bath at 570°C (*1060°F*), since the average value measured in the part is of 645 HV. This hardness is still completely acceptable, since it is located at 58 HRC, within the range of use of this type of steel. Note that, for the same conditions of processing, the hardness of the X160 Cr Mo V12 / D2 would have fallen to approximately 52 HRC.
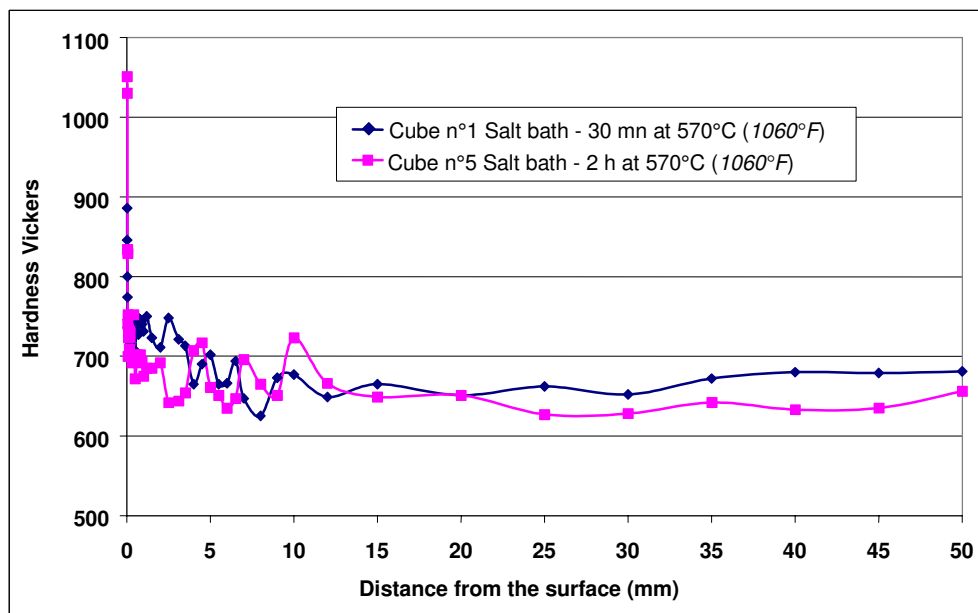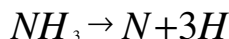
Figure 6 – Hardness of the matrix of TENASTEEL® under 0,5 kgf, after nitriding in Tenifer at 570°C

■ *Gaseous nitriding*

In gas nitriding, nitrogen atoms are provided by the decomposition of gaseous ammonia in contact with a ferrous surface.

$$NH_3 \rightarrow N + 3H$$

The process is carried out at a temperature range between 500 and 570°C (930-1058°F) in a tight furnace with forced convection into which is injected an active gas mixture (NH3 + CH4 or NH3 + N2 or NH3 + NO2 (oxidant activator) + N2 according to the process selected: Nitemper, Trending, Nitroc or Alnat N).
According to the steel grade, nature and composition of the nitrided layer depend on the treatment time, the temperature, the surface of the piece as well as atmosphere and output gas introduced into the furnace.

Comparative nitriding tests were performed on TENASTEEL® and X160 Cr Mo V12 / D2, both heat-treated to 60 HRC. 3 samples of each grade were nitrided at 525°C in the same furnace (company TBI / France). Results are shown in **figure 7**.

Nitrided TENASTEEL® layer appears homogeneous in depth and morphology. On the other hand, that one of X160 Cr Mo V12 / D2 reveals a lot of carbides ande exhibits an irregular depth. Consequently it is easier to measure the thickness of the nitrided layer on TENASTEEL® than on X160 Cr Mo V12 / D2. The values given hereafter are measured at the thickest places (not necessarily those shown in **figure 7**)

For TENASTEEL®, depth of nitrided layers measured by micro-hardness readings or shown on micrographies are coherent, and the values obtained are respectively 60, 80 and120 µm after treatment times of 4, 8 and 16 hours.

For X160 Cr Mo V12 / D2, maximum depth reach only 60, 70 and 80 µm for equivalent treatment times. *Figure 7* shows that in certain zones the nitrided layer drops down to 20 µm after 4h or 40 µm after 8h (respectively 60 and 80 µm for TENASTEEL®)
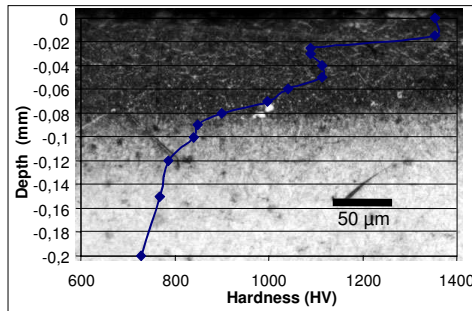
Moreover, due to the quantity of coarse carbides in the nitrided layer of X160 Cr Mo V12 / D2 and its interface with the substrate, a poor adhesion can be expected with possible chipping of the nitrided layer.
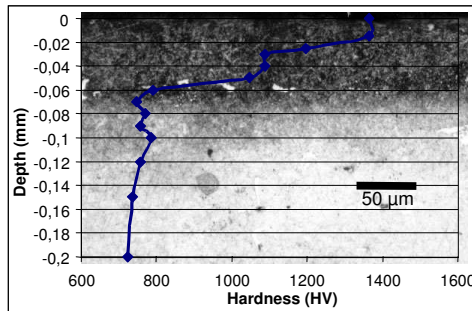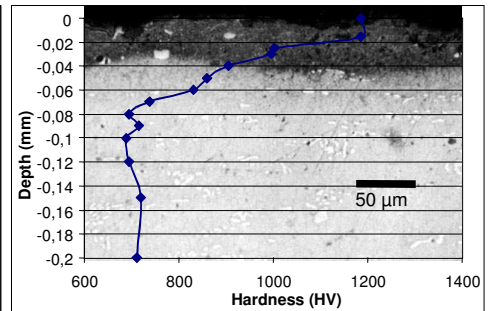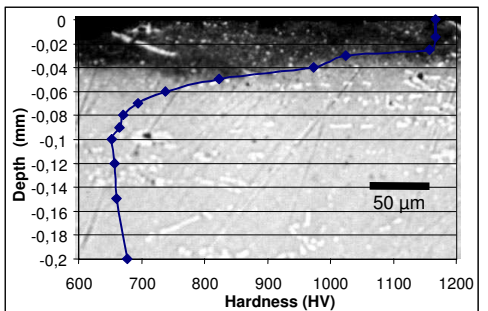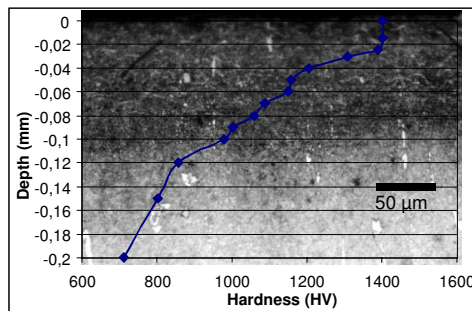
TENASTEEL® – 4 h 00   X160 Cr Mo V12 / D2 – 4 h 00
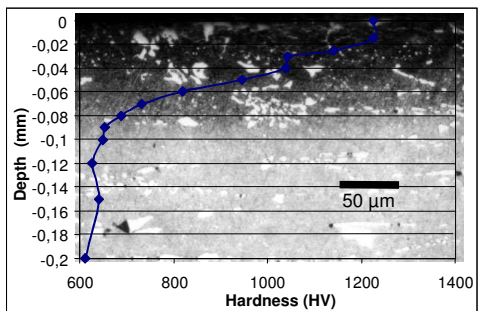
TENASTEEL® – 8 h 00   X160 Cr Mo V12 / D2 – 8 h 00

TENASTEEL® – 16 h 00   X160 Cr Mo V12 / D2 – 16 h 00

Figure 7 – Morphology and characteristics of nitrided layers obtained by gaseous treatment
Comparison with TENASTEEL® – X160 Cr Mo V12 /D2

The second very important point to note is the influence of the hardness of the core of the piece during nitriding.

Figure 8 shows hardness records measured on TENASTEEL® and X160 Cr Mo V12 / D2 in the core of the blocks after 4, 8 16 hours of nitriding at 525°C (*975°F*). Both steels were heat-treated to 60 HRC before nitriding.
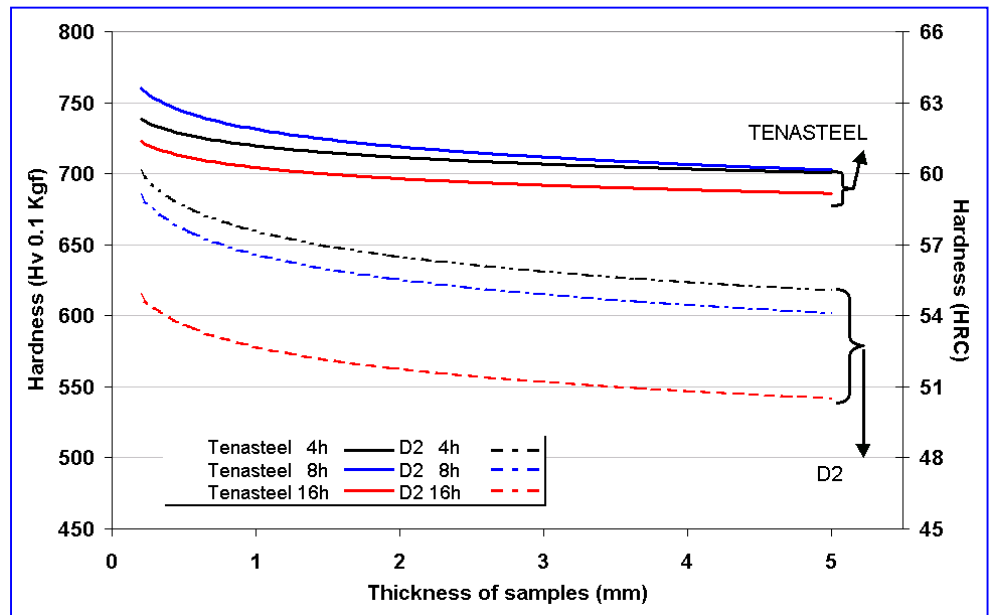

Figure 8 – Comparison of hardnesses TENASTEEL® matrix with X160 Cr Mo V12/D2 matrix after gaseous nitriding at 525°C (*975°F*)

TENASTEEL® keeps it original hardness after gaseous nitriding, a treatment time of 16 H induce only a drop of 1 HRC. On the contrary, the hardness of X160 Cr Mo V12 / D2 is strongly affected as it drops down from 60 to 55, 56, and 51 HRC after 4, 8 and 16 hours of nitriding, respectively.

This softening is not surprising, looking at **figure 8** showing the evolution of hardness versus the holding time at 525°C

■ *Ionic nitriding*

This process has been developed in USINOR group, by the steel-works of Pompey, company now called NITRUVID. The process has two main advantages, compared to the other techniques of nitriding:

▪ Restitution of the geometry and the surface quality

▪ Avoidance of excessive embrittlement of the nitrided layers, as is sometimes the case with the other processes (gas and salt baths)
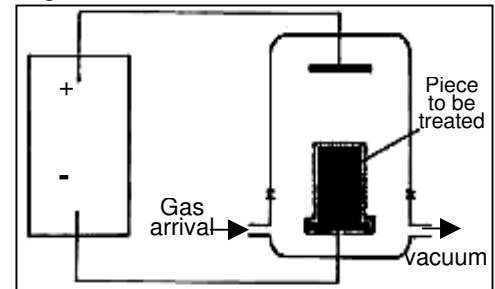
Figure 9 – Schematic diagram of ion nitriding

The principle of the processing is illustrated by **Figure 9**. A pressure from 1 to 5 torrs of gas (N2 + H2 + eventually CH_4 or H_2S…) is fixed in the enclosure. A difference of potential from 300 to 1000 V is applied between the two electrodes causing the formation of luminescent plasma, which contains active ions N+. Under the effect of the strong potential difference, the positive ions are pelted on the surface of the parts places at cathode, causing triple action :

▪ Heating of the parts by dissipation of the kinetic energy of the ions in calorific energy ;

▪ Pickling of the surface of pieces by cathode sputtering $\rightarrow$ Very great surface reactivity ;

▪ Introduction of nitrogen ions necessary for the formation of metal nitrides.

The composition and the thickness of the nitrided layers depend on the temperature treatment of the mixture and gas pressure. The control of these parameters makes it possible to control perfectly the thickness of the outer layer, which can be minimized to avoid chipping, even removed.

Finally, note that this fast processing makes it possible to obtain nitrided layers presenting a toughness significantly higher than that obtained with the other gas or salt baths processes.

Some tests on TENASTEEL® have been conducted in METATHERM Company. Two samples of each grade have been nitrided in same conditions, at 525°C (*975°F*). Results obtained after treatment of 6 and 24 hours are summarized **figure 10.**

Nitrided layers at TENASTEEL® surface seem to be homogeneous both in thickness as in morphology. Nevertheless, as already mentioned, layers on X160 Cr Mo V12/ D2 include many carbides and present a very irregular thickness.

For TENASTEEL®, measurement of thicknesses obtained on nitrided layers through micrographies or by micro-hardness filiation are coherent and give values about 100 and 140 µm for treatments 6 and 24 hours respectively.

For X160 Cr Mo V12 / D2, thicknesses have a maximum of 50 and 100 µm for an equivalent duration of treatment.

TENASTEEL® enables reduction in nitriding time and to obtain a same thickness layer all over the surface of the sheet.

It has to be mentionned that the presence of coarse carbides in the nitrided zone and at the interface with substrate will reduce adhesion and lead to chipping of this layer in the case of X160 Cr Mo V12 / D2.
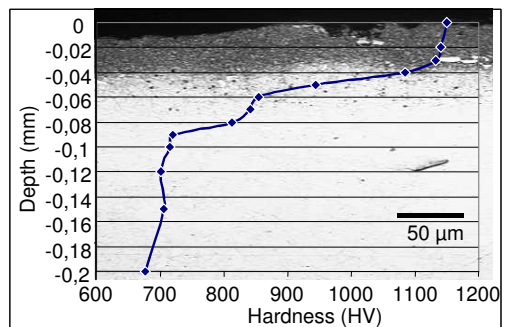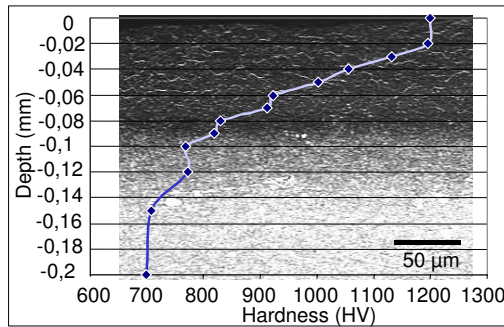
TENASTEEL® – 6 h 00

X 160 Cr Mo V12 / D2 – 6 H 00
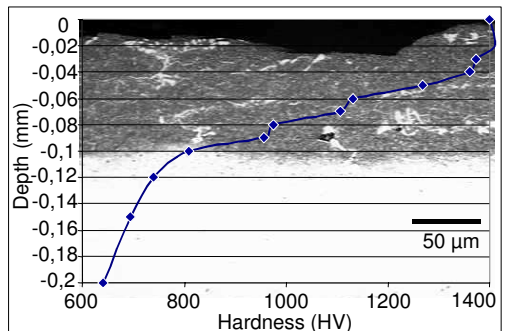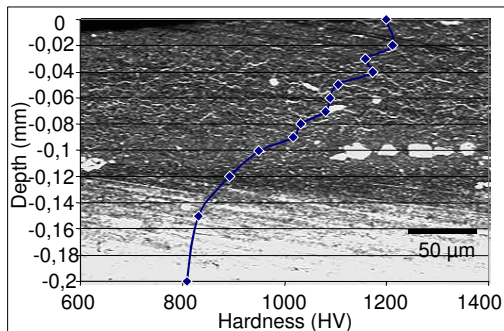
TENASTEEL® – 24 h 00

X 160 Cr Mo V12 / D2 – 24 H 00

Figure 10 – Morphology and characteristics of nitrided layers obtained by ionic treatment
Comparison TENASTEEL® – X160 Cr Mo V12 / D2
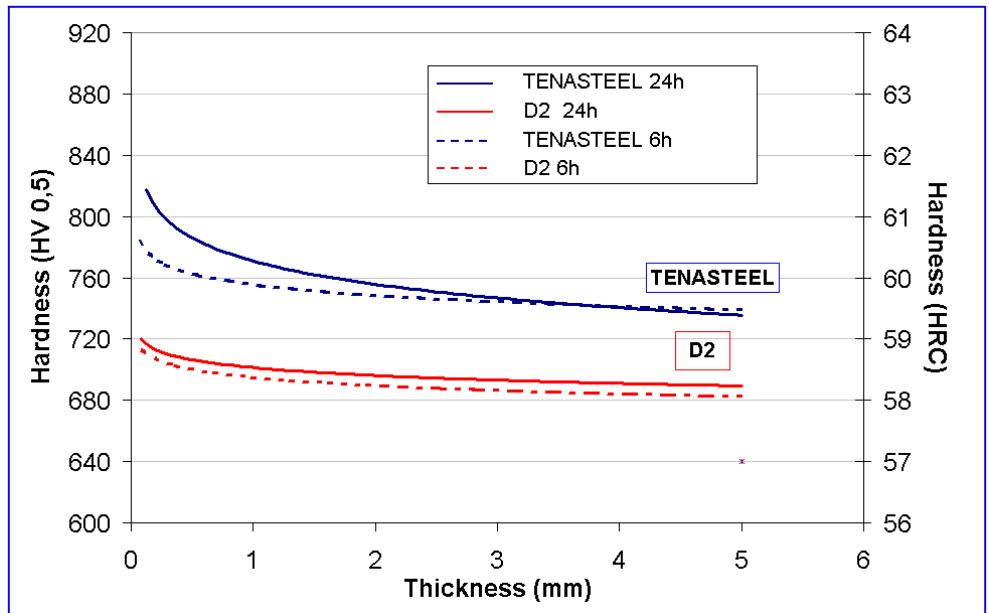
Figure 11 – Hardnesses compared between TENASTEEL® matrix and X160 Cr Mo V12 / D2 matrix – after ionic nitriding at 525°C (*975°F*)

Sheets are heated at only 500°C (*930°F*) for this treatment : TENASTEEL® as well as X160 Cr Mo V12 / D2 save their matrix hardness (respectively about 60 and 59 HRC) as shown **figure 11.**

SUMMARY

Nitriding ability of TENASTEEL® is obviously better than for X160 Cr Mo V12 / D2 as it allows :
- **to obtain homogeneous layers in thickness and in morphology ;**
- **to reduce heating time ;**
- **to avoid chipping of nitrided layers ;**
- **to save the matrix hardness.**

SURFACE COATINGS BY METAL DEPOSIT IN VAPOUR PHASE

The cutting, forming tools, as well as mold elements for aluminum and plastic injection are frequently covered by titanium nitride which reduces to a significant degree the coefficient of friction, and significantly improves the abrasive and adhesive wear resistance.

These coatings, obtained by vapour condensation on the surface of the substrate make it possible to form a metal deposit, which will adhere to the heat treated surfaces. For this type of coating, the preparation of the surface of the substrate is an essential step. Possible problems of adherence can be solved by cleaning and activation of surface.

■ ***PVD (Physical vapour deposition) Process***

PVD coatings are obtained by sublimation, under low pressure, of a solid metal (Ti, Cr for example) in a gaseous medium (N for example). The compound formed (TiN, CrN…) settles on the pieces to be covered as an adhesive thin film conferring new physical and chemical properties.

In this process, the metal atoms coming from a target or a load will settle on the surface of the substrate. These atoms can be produced either by evaporation, or by pulverization ***figure 12***. But whatever the method used, the treatment is carried out at a temperature lower than 500°C not requiring heat treatment of the piece after coating.

Three steps are required for the evaporation process :
- Evaporation of material by heating of a load contained in a crucible,
- Transfer of the evaporated particles from the load towards the substrate,
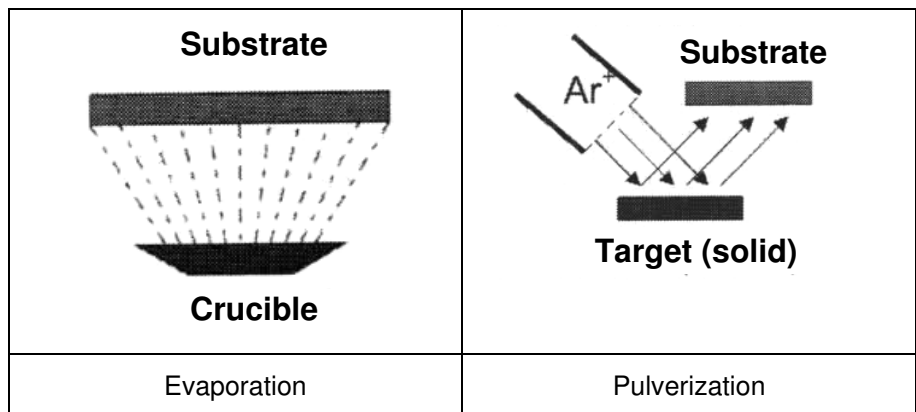- Condensation of these same particles on the surface of the substrate.

Figure 12 – Schematic of the principle of the techniques of metal atom products for PVD coatings.

Pulverization is a physical process of vacuum deposit which uses ions, which pulverize atoms of a target so that they settle on a substrate located facing to this target *(figure 12).*

Considering the performances, the two processes which make it possible to carry out all types of metal deposits, are characterized by the deposit rate (> 1 µm/s in evaporation and < 0,1 µm/s in pulverization), the nature of the target (which can be solid or liquid in evaporation and obligatory solid for pulverization), but especially by the recovery and the soundness of the deposit which will be definitely higher in the case of pulverization.

Industrially, to deposit TiN or TiCN on tools, the processes usually used are the cathodic arc (an electric arc will operate on the target by pulverizing the atoms of this one) and pulverization magnetron (the target is equipped with a magnetic track to increase the output of pulverization). For example, to deposit TiN, it is enough to have a titanium target and to inject nitrogen during pulverization. In dynamic mode, tools are placed on substrates holders which are in rotation in order to ensure a good homogeneity of the deposit.

Test of PVD deposits on TENASTEEL® were carried out at Balzers' shop. The thickness of TiN deposit is 3 to 4 µm, and the hard facing higher than 1500 HV.

■ *CVD (Chemical Vapour Deposition) process*

CVD technique makes it possible to perform, by chemical reactions between species in phase vapour on the surface of the substrate, solid deposits on various metal supports. CVD coating is obtained by a chemical reaction of active gas mixture thermically broken up at a temperature range 800/1000°C and pressures of 10 to 100 mbars.

The solid material is deposited from gas precursors, which react on the substrate. This one is generally heated to provide the energy of activation necessary for the release of the chemical reaction (which can be a simple reaction of decomposition or a reaction of combination) and to allow a sufficient mobility of the atoms to form the desired structure. A carrier gas (which can itself be reactive) generally moves the vapours of the precursors. For example, for TiN, TiC and TiCN deposits, the reactive gas is Ti Cl_4, in mixture controlled with N_2 or/and CH_4.

Energy necessary to the chemical reaction can be provided by more sophisticated processes like:

▪ *Plasma,* in the case of the PACVD - Energy is brought to reactive gases either by exciting them by an electric discharge or by exciting the carrier gas (Ar) from which the accelerated ions transfer their energy to the reactive species (plasma). The substrate must nevertheless be heated, though less extremely than in the conventional process, to ensure a mobility and sufficient reactivity of the atoms.

▪ *Laser* for LACVD. The energy of laser radiation is used either to activate (or break) the gas species (photolysis), or to heat the substrate in order to promote the reaction of surface. Moreover, the laser irradiation of the substrate only heats its surface avoiding possible damage in the core)..

With a long distance from the surface of the substrate, the concentration of the gas precursors does not vary according to the distance to surface. On the other hand, near the surface, this concentration decreases due to the consumption of the reagent. The concentration of the product of decomposition (gas residue of the chemical reaction) undergoes an opposite variation. The gas layer in which concentrations vary is called boundary layer.

Figure 13 shows that the kinetics of the process depends on several steps :

(1) Convection of the gas reagent (dynamic flow)

(2) Diffusion of the reagent towards the substrate

(3) Adsorption of the reagent on the chemical substrate

(4) Reaction of the species adsorbed

Figure 13 – various steps of process CVD

(5) Desorption of the gas products of the reaction

(6) Diffusion of these products through the boundary layer
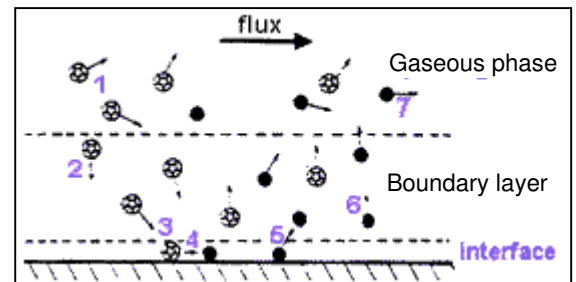
(7) Evacuation of gases of the system

Coating has a very good adherence, higher that one obtained for PVD deposits. This is due to the contact between the substrate and the deposit because of the high temperature of the processing. In addition, different advantages of this technique can be noted :

- The high deposit rate : can reach 1000 to 10 000 angströms per minute ;
- The control of the stoichiometry, the morphology, the crystal structure and the orientation of growth which can be adjusted by control of the parameters of deposit ;
- Uniform recovery of complex and hollow forms ;
- The possibility to obtain deposits of high purity with the help of a thorough purification of the precursors.

The principal disadvantage of the technique is of course the temperature of work ranging between 800 and 1000°C (*1470-1830°F*) which requires a final vacuum hardening by quenching and tempering of pieces after coating CVD. The knowledge of the dimensional stability of the substrate during heat treatments is then essential to obtain the final dimensions of parts. The measurements taken on plates of TENASTEEL® of 100 x 100 x 25 mm can be seen ***figure 14.***
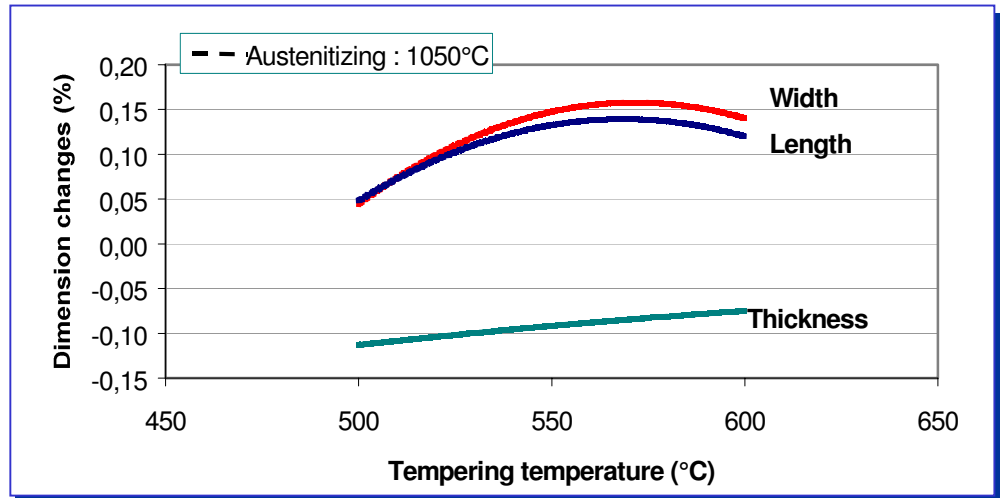
Figure 14
Dimensional changes during processing of hardening and double tempering of TENASTEEL®

Tests of deposits CVD on TENASTEEL® were carried out by VST in Germany. A mixed coating TiC/TiN has been deposited with thicknesses from 3 to 5 µm each. The first layer of TiC allows an excellent fixing of the coating by migration of carbon in the substrate, then a transition course made up of TiCN is formed before the very hard layer of TiN is deposited. The total thickness of coating was 10 to 12 µm and its higher surface hardness close to 2400 HV. For this type of coating the greater advantage of TENASTEEL® compared to X160 Cr Mo V12 / D2 is due to the smoothness and the distribution of carbides. Indeed, the presence of large chromium carbides in the interface between the substrate and the coating decreases the adhesion of this one.

SUMMARY

Coating adherence is improved on TENASTEEL®, due to smaller size of carbides.

Due to its chemical analysis, TENASTEEL® offers as improvement in weldability compared with classical D2 steel. The important carbon reduction of this new grade allows more possibilities of welding repairs.

In order to measure this characteristic, Research Center instituted filled notch simulation or overlay welding process.

This process represents the majority of possible maintenance, so GTAW process has been used as reference.

Following experiences, the main important parameters can be underlined :
- Preparation of the welds,
- Choice of welding consumable,
- Choice of welding parameters,
- Condition of heating of the pieces.

SURFACE PREPARATION

■ Of course, the welded zone has to be clean and free of any crack.
   A dye penetrant inspection before welding is recommended.

■ If the ratio P/l between depthand width of the notch is greater than 1, a hot cracking phenomenon will probably occur in the middle of the weld bead.
   To avoid this, it is preferable to enlarge, by grinding, thezone to be overlaid, or filling the bottom of the notch with a low alloyed welding product.

CHOICE OF CONSUMABLE

Welding consummable selection is a function of required properties of the welded zone:

- *Case of homogeneous repair*
  (Need to guarantee equivalent hardness) :

Reference	Producer	Hardness obtained
UTP A696	BTW	60-64 HRC
UTP A 73 G2	BTW	53-58 HRC
DURANIT M10	BTW	60 HRC

▪ *Case of heterogeneous repair*
(allows to reduce risks)

Overlay with stainless wires : limited preheating

Reference	Producer	Hardness obtained
ER 307	Choose yourself	Not significant
ER 312	Choose yourself	

As mentioned in the Chapter "Surface preparation", a solution is to fill with a soft steel and finish last layers with a hard facing steel.

Above mentioned products for an homogeneous repair are available ; following material can also be used :

Reference	Producer	Hardness obtained
UTP A DUR 600	BTW	55-60 HRC
ROBODUR K 600	Automatic welding	60 HRC
R 600 B	FP Welding	60 HRC

CHOICE OF WELDING PARAMETERS

GTAW process is the optimum for repairing TENASTEEL®, because hydrogen introduction is low.

A welding energy of about 1,5 kJ /mm allows a good compromise between weld puddle cooling and HAZ.

Excessive energy can cause important residual stresses.

A short arc length has to be maintained ; in this case, no melting bath pollution and an efficient gaseous protection is guaranteed, so that constant parameters all along the operation.

Pure Argon is the best gas to be used for this application.

Heating condition :

Pre and Post heating are necessary to protect the piece from an eventual risk of cold cracking.
Our tests gave the following conditions :
Pre-heating: 250° mini
Post-heating: 250° mini

Of course, these conditions have to be modified in the case of using specific welding products (chromium casting, stellite…).

For these thermal operations, we recommend the use of ceramic thermocouples.
As homogeneity of temperature must be perfect, the use of gas burners has to be strictly controlled.