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Effects of the Use of Master Alloys on the Sintering of Mn Steels
Efectes de l'ús d'aliatges mestres en la sinterització d'acers al Mn

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Als meus pares i al Nil

A la Maria

A tots els meus professors/es i companys/es

Report

CONTENTS

1. GLOSSARY

Master Alloy (MA): In the context of pulvimetalurgy, it is a powder with a high concentration of elements designed to be added to a base powder to provide the chemical composition, the level of properties and microstructure desired after the sintering process.

Solid State Sintering (SSS): Sintering process where solid state diffusion is the main mechanism of matter exchange between particles.

Liquid Phase Sintering (LPS): Sintering process where a transient liquid phase is formed and fills the space between pores to weld the main material's particles together.

Uniaxial Tensile Strength (UTS): Strength required to break a specimen apart when testing its traction behaviour.

C: Carbon

Cu: Copper

Mn: Manganese

Cr: Chromium

Ni: Nickel

Si: Silicon

Mo: Molybdenum

2. SUMMARY

When manufacturing sintered steel parts there is the option of adding alloying elements that improve the mechanical, functional, dimensional and wear properties of the component. This is the case of elements such as Mn or Si, which can provide a substantial improvement of the mechanical properties of a steel while maintaining a low cost given the abundance of these in the Earth's crust. Their use, however, is conditioned in the pulvimetallurgy industry given the affinity for oxygen shown by both elements, producing oxides that weaken the sintered components. One of the solutions developed to incorporate these elements into powder mixtures for sintering is the use of master alloys that allow the reduction of the chemical activity of the elements thus avoiding the formation of oxides.

In this study, tests were carried out with four master alloys with different compositions of Mn and Si in order to study their behaviour during sintering and the properties they bring to sintered steel. With this objective, several mixtures containing different master alloys are prepared to produce sintered specimens at temperatures normally used in the manufacturing of sintered components. These specimens were used for the mechanical, chemical and microstructural characterization of steels, which will allow the study in greater depth the processes and changes that master alloy particles suffer during sintering, as well as understanding how these processes affect the properties obtained. A range of graphite additions were used in combination with the different master alloys in order to see how the presence of carbon in varying amounts affects the sintering mechanisms.

The conclusions of this project paint a bigger picture of the behaviour of Mn and Si introduced in the form of master alloys and their interaction with the rest of the elements of the mixture. In addition, the manufacture of these specimens in industrial sintering conditions allows a first look at the viability of these master alloys for use in the manufacturing of sintered components.

3. RESUM

A l'hora de fabricar peces d'acer sinteritzades existeix l'opció d'afegir elements d'aliatge que milloren les propietats mecàniques, funcionals, dimensionals i al desgast del component. És el cas d'elements com el Mn o el Si, que poden proporcionar una millora substancial de les propietats mecàniques d'un acer mantenint un cost baix donada l'abundància d'aquests en l'escorça terrestre. El seu ús, però, es troba condicionat en la industria de la pulvimetal·lúrgia donada l'afinitat a l'oxigen que presenten ambdós, produint òxids que debiliten els components sinteritzats. Una de les solucions desenvolupades per incorporar aquests elements a les mescles de pols per a la sinterització és l'ús d'aliatges mestres que permeten reduir l'activitat dels elements i evitar d'aquesta manera la formació d'òxids.

En aquest estudi s'han realitzat proves amb quatre aliatges mestres amb diferents composicions de Mn i Si amb l'objectiu d'estudiar el seu comportament durant la sinterització i les propietats que aporten a l'acer sinteritzat. Amb aquest objectiu s'han preparat diverses mescles que contenen els diferents aliatges mestres per preparar provetes sinteritzades a temperatures usualment emprades en la fabricació de components sinteritzats. Aquestes provetes s'han utilitzat per a la caracterització mecànica, química i microestructural dels acers, que permetrà estudiar en més profunditat els processos i canvis que sofreixen les partícules d'aliatge mestre durant la sinterització, així com entendre com afecten tots aquests processos a les propietats obtingudes. Un rang de composicions de grafit s'ha afegit en combinació dels diferents aliatges mestres per veure com la presencia de carboni en diferents quantitats afecta aquests mecanismes de sinterització.

Les conclusions d'aquest projecte aporten nous coneixements al comportament del Mn i el Si introduïts en forma d'aliatge mestre i la seva interacció amb la resta d'elements de la mescla. A demés, la manufacturació d'aquestes provetes en condicions de sinterització industrial permet obtenir una primera ullada a la viabilitat d'aquests aliatges mestres en la fabricació de components sinteritzats.

4. PREFACE

4.1. PROJECT ORIGIN

This end-of-degree project is part of a research project developed at AMES PM TECH CENTER for the design of master alloys with the aim of reducing the alloying elements necessary to obtain the standard mechanical properties of sintered metals , as well as introduce oxygen-sensitive elements with an improved performance, both energetically and raw materials-related.

This specific project consists of an optimization of mechanical properties based on the conditions of sintering and thermal treatments most used in the production of sintered steel components in AMES. The evolution of the microstructure under these conditions has also been studied in order to understand each master alloy system (diffusion patterns, phases and microstructures, or dependence between properties and concentrations of alloy elements, for example).

All this encompasses the last stage of an initial design of master alloys and their validation for testing at an industrial level. This will allow the design and production of a new series of master alloys optimized for future characterization and testing.

4.2. MOTIVATION

Since the introduction of the first powder metallurgy manufactured components in 1937, the industry has constantly evolved. The great amount of compositions, processing conditions and production processes that have been developed in the last decades are proof of that.

Nowadays sintered steels have a leading role in the automobile industry given the advantages they present in terms of productivity, costs and properties. However, the increasingly high requirements of this industry demand parts with greater properties at a lower cost.

In order to meet these demands, the industry must consider strategies that allow dealing with problems such as sensitivity to oxidation, lack of homogenization and the presence of porosity, the main intrinsic problems of the sintering process. In addition, the use of alloy elements with high and/or unstable prices presents another factor that can affect the expansion of sintered metals in the metallurgical industry.

Master alloys allow the introduction of elements through a powder with a high concentration of these. Their use has the advantage that it allows the addition of elements that initially can pose an added degree of difficulty when they are added to the mixture due to their high affinity for oxygen, but which on the other side can provide a substantial improvement of properties at a low cost and with a high availability. This is the specific case of Mn and Si, which provide a better properties/cost compromise compared to other more commonly used elements, such as Ni, Mo, P or Cu (1). However, the main advantage of master alloys is the flexibility when formulating alloy systems and adapting the design to the requirements of the component to be manufactured. Additionally, the use of master alloys improves compressibility due to the high hardness level Mn presents, which would be very difficult to compact; prealloying it with Fe reduces those levels and eases compacting.

Initially, the concept of master alloy was born with the aim of introducing elements with high affinity for oxygen such as Cr, Mn, V or Si among others. The alloying of these elements with others of low sensitivity to oxygen forming a pre-alloy provides good protection against oxidation and is also an efficient way to alloy these elements with the steel. So far, the Fe-Mn-C, Fe-Cr-Mn and Fe-Mn-Si (-C) systems have been explored; However, conventional elements in the powder metallurgy industry are perfect candidates for the design of new master alloy compositions.

The use of master alloys for steels presents an additional advantage when they are designed with a melting point below the typical sintering temperatures. During sintering, the master alloy melts and forms a liquid phase that accelerates the processes of diffusion and porosity elimination while promoting the distribution of the alloy elements. It must be taken into account, however, that despite presenting an ideal environment for the new introduction of new alloy systems, liquid phase sintering involves problems with dimensional control, secondary porosity or reactivity with the solid phase, which must be analysed and properly solved to obtain high performance.

Last but not least, the introduction of master alloys in sintered steels may offer a means of reducing the total amount of alloying elements to obtain the same properties as a conventional sintered steel. This is an indispensable requirement to reduce the costs of sintered steels. The current computer tools based on thermodynamic calculations make possible the prior simulation of alloy systems for cheaper production.

5. INTRODUCTION

5.1. OBJECTIVES

The objectives of this project encompass the mechanical, chemical, microstructural and compositional characterization of Mn-based master alloy systems in typical industrial sintering temperatures, atmospheres and thermal treatments. In this way, after being able to understand the processes and mechanisms that take place during sintering, as well as analysing the mechanical properties of the tested specimens, the viability of these new systems will be assessed for their use in the industry and better criteria will be taken into account for the design of future master alloy systems.

For this specific part of the project, several objectives have been established to limit the scope and build the foundations for future studies on the matter:

- Prepare Fe-MA mixes for industrial sintering at different temperatures typically used in the powder metallurgy industry, taking into account and controlling the different conditions that take place in the sintering furnaces (time, atmosphere…). With this, testing specimens will be obtained that represent the evolution and changes for several temperatures and conditions.
- Dimensional, mechanical, chemical, metallographic and compositional evaluation of said specimens in order to characterize the processes that occur during sintering.
- Evaluation of the properties tested and consideration of the commercial use of the master alloy systems.

5.2. PROJECT SCOPE

The scope of this project includes the preparation, sintering and study of several mixes containing master alloys designed to help us better understand the addition of several alloying elements such as Mn, Si, Ni or Cr that historically have presented several problems when it comes to their addition in sintering mixes, whether because of their affinity for oxygen or because of other problems faced when industrially producing them. It also includes all the necessary testing of the specimens in order to paint a better picture of the properties obtained through the industrial sintering of these mixes.

There are some aspects that will be necessarily limited due to technical limitations. First, the difficulty of producing new master alloys in low quantities due to the high cost of equipment and materials is the most limiting aspect of this project. This means that the selected master alloy compositions will remain unmodified throughout the whole study. Modifications will have to be left for future stages of the project, and these will need to be properly justified and designed for production.

Finally, all the testing is limited to the available resources at AMES facilities where the project takes place (leaving out of reach any experiment that requires any non-available equipment).

6. BACKGROUND

6.1. POWDER METALLURGY

Powder metallurgy is an industrial process where fine metal powder is pressed into a desired shape (pressing) and then heated in a controlled atmosphere (sintering) to obtain a metallic component.

The year 1829 marks the beginning of the industrial production of sintered platinum parts, which was a very difficult process due to its high melting temperature (1770ºC). In WWII the mass production of sintered components became of major importance to satisfy the growing demand of the automobile and war industries.

Powder metallurgy has demonstrated its importance in the manufacturing of components that would otherwise be unattainable (or hardly attainable) with other processes such as machining or casting.

The importance of this technique remains in the possibility of manufacturing high quality components with complex geometries (all of this with near-net-shape), better properties thanks to higher homogeneity and better grain size control, and a lower price as a result of less waste production.

The process of powder metallurgy can be divided in four phases: material preparation, mixing and pressing, sintering, and cooling and finish. There is also the possibility of applicating a thermal treatment if the component requires it.

Powder metallurgy presents several advantages, including important environmental improvements such as:

1. Powder metallurgy utilizes more than 97% of the original raw material in the finished part. This means nearly zero waste material.
2. The parts obtained have an excellent finish with only one manufacturing process.

3. Feasibility of mass production due to the easy automatization of processes.
4. A sintered component has a comparable quality to those obtained through casting or machining, at a lower price for several applications.
5. Enables the obtention of several metal alloys that improve the material's mechanical and chemical properties, as well as a great variety of microstructures.
6. Allows the formation of assemblies using sintered components with different shapes and compositions.
7. Allows the obtention of refractory materials with high melting point that cannot be obtained through other processes.
8. Mechanical properties are comparable or superior to those obtained in parts produced by other processes.
9. Guarantees less energy consumption.
10. The recycling of sintered components is usually fairly easy.
11. The use of sintered metals reduces the impact of mineral exploitation by 40% and reduces the impact to global warming by 25% compared to the casting process.
12. Reduces the influence of environment acidification (60%) and the influence on environment toxicity (70%) compared to the casting process.
13. Gives a strict control on the porosity of the component.

On the other hand, powder metallurgy also presents some disadvantages:

1. High initial cost of equipment.
2. Some limitations on the shape and size of the components which can be produced.
3. Welding powder metallurgy components presents some challenge, and only some techniques are viable for that purpose.

6.1.1. Powder production

The powder metallurgy process begins with the production of a metallic powder, whose chemical composition will depend on the characteristics of the desired material. This powder can be pure metal or an alloy.

The initial powder can be obtained in several ways. The most common are:

1. Atomization: powder particles are obtained from molten metal (a and be being the most commonly used):
    a. Water atomization: Water is blown into a flux of molten metal. Produces irregular particles.
    b. Gas atomization: Gas is blown into a flux of molten metal. Produces spherical particles.
    c. Plasma atomization: A wire feedstock is fed into a plasma torch that, with the aid of gases, atomizes the metal. Gives high quality and extremely spherical particles, but it is limited to metals that can be formed into a wire feedstock.
    d. EIGA (Electrode Induction melting Gas Atomization): A film of molten metal flows downwards into a gas stream for atomization. Therefore, material does not come in contact with either crucible or electrode during process.
    e. PREP (Plasma Rotating Electrode Process): Similar to EIGA but the feedstock comes in contact with plasma instead of gas. The powder obtained is extremely spherical, but yields are limited to 100 microns, so price can be high.
    f. Centrifugal atomization: A good compromise between gas and plasma atomization. Best suited to larger batch sizes of less reactive low melting temperature alloys.
2. Chemical methods: Mainly through the reduction of metal oxides.
3. Plasma spheroidization: This technology ensures perfectly spherical powders and a low contamination.

Depending on the manufacturing method the obtained powder will vary in size and shape. The sizes used in the powder metallurgy industry are compromised between 10 and 400 microns, being 100 microns the most common size. These differences in shape and size will affect the final product during and after the pressing phase.

The powder can later be mixed with alloying elements to achieve a desired composition, with solid organic lubricants, or even special additives, such as binders that confer a better green strength and that will later be eliminated in the furnace. In any case, the final result must have a homogeneous distribution.

The powders mixed in this process come from different materials where their characteristics complement one another to improve the quality of the component. These characteristics can be:

1. Shape: As stated above, the particle can be spherical, irregular, flat…
2. Size distribution: The size of the particles will greatly affect the behaviour of the powder itself before and during the sintering process, as well as the properties of the final product such as density or porosity.
3. Flowability: It is the property that measures the ability of the material to flow through one part to another in the pressing die.
4. Reactivity: Fundamentally refers to the capacity of reacting with other elements.
5. Compressibility: It is the relation between the apparent density and the density obtained after the pressing. It varies depending on the particle size and shape and will have a great effect on the mechanical properties of the part.
6. Density: It is generally desirable to maintain a constant density throughout the whole component to ensure its strength and quality.

The elements that make up the final material can be added in several ways:

1. Mixing: The alloying element powder is directly added to the base powder. This method makes it easier to obtain higher compressibility, therefore obtaining higher values of density; however, some zones can present a heterogeneous distribution of alloying elements.

2. Pre-alloying: This method uses alloying elements previously alloyed with the base material. This one ensures high homogeneity, but the compressibility rate is reduced due to higher hardness values depending on the elements used (2).
3. Master Alloy: Consists of a prealloyed powder rich in alloying elements that is added in small quantities to the base material in order to diffuse it in the sintering phase. This last method is the main theme in this project and presents several benefits that will be discussed later.

6.1.2. Compacting

The powder is introduced into a die shaped like the negative of the component to manufacture. This die must have great dimensional accuracy and durability in order to withstand the high pressures of the press. The presses that are used to compact the powder are usually placed in the 200-1500 MPa spectrum of pressures depending on the density that has to be achieved, but in some cases greater pressures might be required.

This whole compacting process must be subject to statistical quality checks via SPC checks. It is of great importance that the compacting process ensures sufficient contact between metal particles so that diffusion mechanisms in the sintering process take place and the desired results are achieved.

The relation between the final properties of the component and the pressure exerted makes it so that, the higher the pressure, the better the results obtained. That way, if the pressure exerted is higher, the following is achieved:

1. Higher density, near to 100% in relation to the bulk material.
2. Better resistance when in green state.
3. Better mechanical properties when the part is sintered.

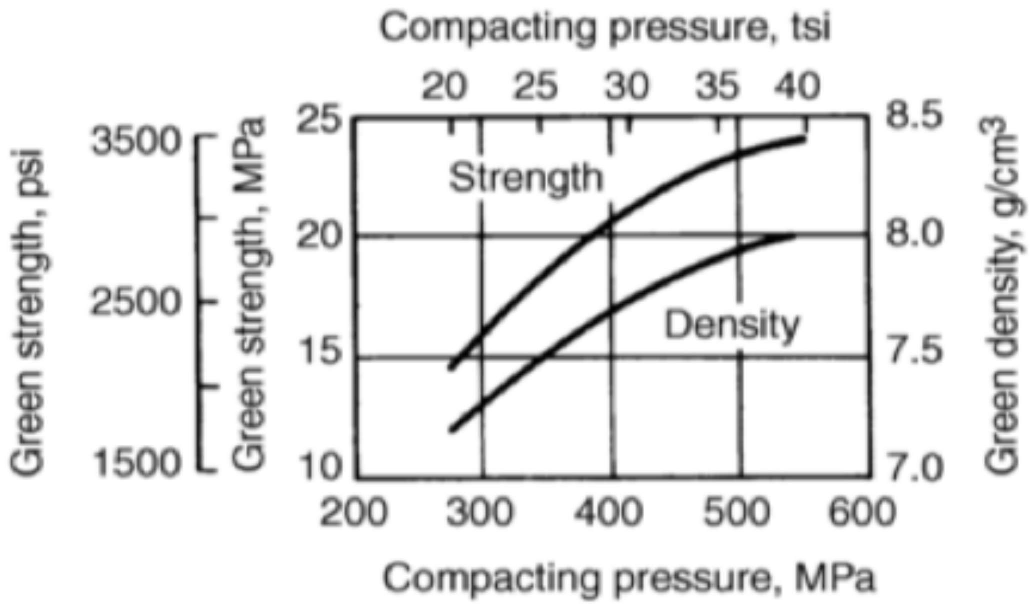

Figure 1 Relation between compacting pressure and properties for steel

6.1.3. Sintering

Sintering is a thermal process where metal particles are heated to temperatures under the melting point (70-80% of that). This temperatures range between 750ºC and 1300ºC, but the most common one is 1120ºC. This temperature promotes atom diffusion and welds the particles together, creating sintering necks where alloying elements can freely travel.

As a result, sintering provides high quality components, with great dimensional stability, with a certain degree of porosity and completely functional.

The driving force of sintering mechanisms is the reduction of surface free energy produced from the decrease of surface area and the replacement of solid-vapour interfaces for solid-solid interfaces. This effect is greatly increased with the reduction of particle size. There are two basic types of sintering mechanisms: solid phase sintering and liquid phase sintering.

6.1.4. Solid state sintering

During the sintering process the powder particles join forming bonds with the surrounding particles due to the increase in temperature, that eases the atom exchange and the formation if sintering necks (Figure 2). This phenomenon occurs at temperatures lower than of those of melting and accelerates as the temperature raises. There are several diffusion paths that atoms take in this sintering process (up to six) being sintering neck condensation/solidification and neck surface diffusion the most important ones.

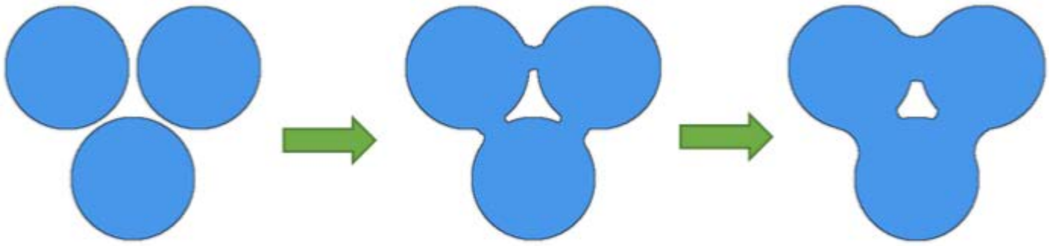

Figure 2 Solid phase sintering (3)

6.1.5. Liquid phase sintering

The addition of an element with a melting temperature lower than the sintering temperature will produce a transient liquid phase that will be beneficial in certain circumstances. Some master alloys can be designed to obtain a transient liquid phase, as well. This liquid phase allows the molten material to be evenly distributed throughout the whole grain grid increasing the contact surface (Figure 3). Moreover, if the molten material is soluble in the solid material, the molten will diffuse into the solid one after being distributed. This will also lead to the formation of pores where the liquid material was, phenomenon known as secondary porosity. When a master alloy is designed to form a liquid phase, several aspects must be taken into account, such as wettability or the solubility with the base powder to ensure that the master alloy will diffuse into the matrix.

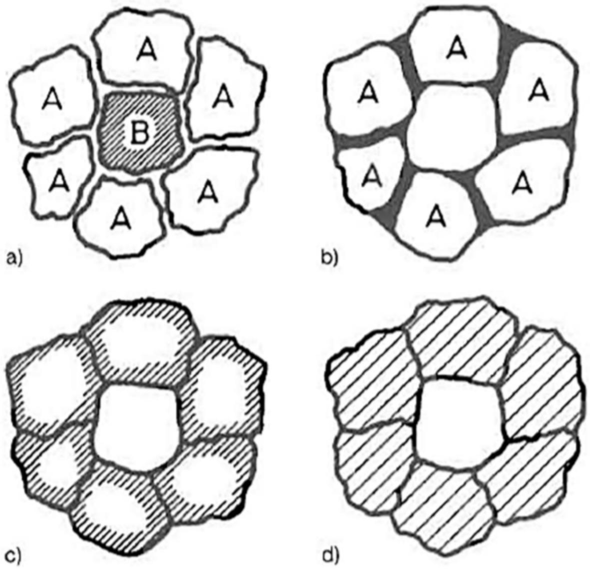

Figure 3 Liquid phase sintering mechanism (4)

6.1.6. Finish

Sintered components often might need a final touch to ensure that some complicated components meet the tolerance established, this can be done through almost any machining operation such as turning, milling, drilling, tapping, grinding, lapping, grinding, polishing, etc. Deburring can also be applied to eliminate undesired edges and achieve lower rugosities. Cleaning and vapour treatments are also optional procedures: cleaning is used to remove any residue or organic substance present from past operations, while a vapour treatment can be used to produce controlled corrosion to the component; this will form a magnetite layer to protect from further Ambiental corrosion.

6.1.7. Thermal treatments and coatings

Sometimes, a certain application requires a harder surface, like gears. Thermal treatments are a good option to achieve these higher values in surface hardness. Typical thermal treatments are tempering, carbonitriding or case-hardening, among others.

Sintered components also accept almost any kind of conventional coating, such as Chrome plating, zinc plating, or PTFE plating, among others.

6.2. Sintering aspects

6.2.1. Time and temperature

Time and temperature that sintering parts spend in the furnace heavily condition the microstructure and interactions between phases. Industrial furnaces conduct a heating segment, followed by an isothermal segment and finish with a cooling segment where temperature decreases slowly with the part's temperature.

The typical sintering temperature is 1120ºC and the typical time is comprised between 15 and 90 minutes.

Several studies at high temperature sintering report that an increase of 80ºC provides an improvement to the material's porosity, achieving rounder internal pores. This provides an important upgrade to the impact resistance of the component, as well as a slight improvement to the ductility of the material. However, high temperatures can also be counterproductive with the hardness levels of the component if they are not properly controlled. High temperature sintering also permits shorter sintering cycles due to the higher speed of diffusion mechanisms. Lastly, higher temperature sintering allows the design of master alloys with higher melting temperature, providing the possibility of more element variety.

6.2.2. Atmosphere

In sintering furnaces, the atmosphere must be controlled in order to prevent the corrosion of the component or other chemical interactions (5). There are mainly three types of atmosphere employed varying on the desired results:

1. Reductive-decarburizing atmosphere (6): Mainly pure hydrogen or dissociated ammonia, its high H2 content eliminates oxygen through water vapour formation and carbon through methane formation, producing a drop in C and O contents.
2. Reductive-carburizing atmosphere (7): Same as the above, but the addition of CO confers a rise of the carbon content in the part with the same reduction of oxygen content.

3. Neutral atmosphere: Generally pure nitrogen this atmosphere does not interact with the component and keeps the component intact, preventing the oxidation.

It is also common to combine percentages of these atmospheres to benefit from different characteristics at once. The effect of these atmospheres has been thoroughly studied in previous works (8). Technical limitations in sintering furnaces, as well as gas changes for different temperatures, prevent the use of an all-around optimal atmosphere, having to sacrifice some aspects in benefit of others.

6.3. MASTER ALLOYS

6.3.1. The Master Alloy concept

In the context of powder metallurgy, a master alloy is a powder with a high concentration in alloy elements specifically designed to be added to a base powder in order to provide the chemical composition, the level of properties and the desired microstructure after Sintering. The master alloy is an excellent vehicle for introducing alloy elements into ferrous alloys, and in the last decade, this alloying method has received increasing interest in the field of sintered steels. Mainly, its boom is linked to two singularities:

1. The wide flexibility when selecting the chemical composition of the alloy. This allows the alloy to be designed specifically to meet certain requirements. It is especially interesting that in the form of a master alloy it is possible to incorporate elements of high affinity for oxygen, such as Mn, Si, Cr, which favour a great increase in properties (greater hardenability) at a low cost, but whose use in sintered steels are limited by sensitivity to oxidation. The combination of these elements in the form of prealloy with Fe and/or C minimizes these problems and enhances improvements in the steel. In addition, the composition of the master alloy can be changed in order to promote its fusion and the formation of a liquid phase during sintering, which accelerates the diffusion and densification processes.

2. The possibility of improving the properties of sintered steels obtained from other alloying methods, i.e. prealloyed or alloyed powders by diffusion. In particular, the use of master alloys does not modify the compressibility of the iron powder, and therefore, allows to face the main disadvantage of prealloyed steel powders. In addition, the slow diffusivity of the alloy elements (Ni, Mo) in steels alloyed by diffusion can be solved with master alloys of low melting point, which promote the appearance of a liquid phase with a good distribution that serves as a medium of transport of the elements during the sintering phase.

6.3.2. Alloy design

To design the master alloys composition, the *Thermocalc* software was used. This software lets the user create phase diagrams for any said combination of metals using thermodynamic simulations. Specifically, for this purpose, the SSOL 4 database was used. The aim of the composition is to be able to add a certain concentration of an element while achieving a melting temperature of under 1120ºC, the most common sintering temperature in the industrial sintering process.

All of these calculations were done at the beginning of the whole project and have already proven valid with an actual laboratory characterization in previous works (9).

6.4. ALLOYING ELEMENTS IN POWDER METALLURGY

As seen above, master alloys can be composed of several elements that, once introduced in the sintering phase, will provide different characteristics, and those might be advantages or not. The following elements stand out due to their recurrent use in powder metallurgy or the properties they provide to steel after sintering.

6.4.1. C

Carbon is introduced in iron to produce steel, the most used alloy in the entire planet. It is used to raise tensile strength, hardness and wear resistance.

When introduced in elemental form, carbon diffuses rapidly at 800ºC and moves throughout the whole part during sintering thanks to its capacity to move between interstices in the iron lattice, favouring a homogeneous concentration throughout the whole body of the part. The concentration of ferrite and pearlite, for example, can be controlled with the carbon concentration.

Initially, carbon was introduced in master alloys to form carbides and protect other elements against oxidation, but in exchange that would raise the necessary temperature during sintering.

At high temperatures, near the 1000ºC mark, carbon acts as a redactor agent allowing the reduction of oxides present in the material (we can check this on Ellingham diagrams) and improving diffusion of other elements. On the contrary, due to the reduction process, some carbon will be lost in the material causing decarburation, that can be incremented in the component edges if the sintering does not take place in a controlled atmosphere.

6.4.2. Cu

Copper stands out for its low melting point (1083ºC), just under the typical sintering temperature of 1120ºC, facilitating its distribution through the grain limit (10). Besides, the appearance of liquid phase promotes the rapid diffusion that contributes to a better densification of the material in exchange of a general swelling of the component and secondary porosity phenomena where copper particles were found before.

Cu incorporation in master alloys is often used to reduce the melting point and promote the appearance of a transitory liquid phase that helps the diffusion of other elements present in the master alloy.

6.4.3. Mn

The addition of manganese confers steel with a great improvement of its mechanical properties, hardness and resistance. Its low melting point (800ºC) forms a gas phase which in part helps the Distribution throughout the whole material but, on the other hand, due to its high affinity with oxygen, fosters the formation of oxides surrounding the steel particles, forcing the use of heavily controlled atmospheres. It is also important to remind that due to its abundancy in earth, manganese is one of the cheapest alloying elements for steel (11).

Its presence in master alloys provides steel a great improvement on its properties but its affinity with oxygen leads to the formation of oxide layers around the master alloy particles hindering the diffusion of other elements and even the sintering of the component. This effect can also be seen greatly increased due to the ease of Mn to escape the master alloy particle in gas state at 800ºC.

6.4.4. Cr

Chromium is an element that provides one of the greatest improvements in mechanical properties steel, especially hardness. The problem with it is that its high affinity with oxygen promotes the formation of oxides, so the risk of oxide appearing during the sintering phase is rather high. To palliate this Cr is introduced through prealloyed mixes or master alloys to provide a greater chemical stability and it is sintered in reducing atmospheres to difficult oxidation.

6.4.5. Ni

Nickel is an alloying element capable of heavily increasing the ductility of a material and the fatigue resistance when introduced as master alloy. Its use is restrained to its high price and its low diffusion coefficient that stops it from combining properly with steel forcing to increase the temperature and time of sintering, as well as originating heterogeneities in the material.

6.4.6. Si

Silicon presents two great advantages as an alloying element: the first one is that confers steel with a great improvement in hardness, the second one is its cost; being the most common element in earth’s crust translates to low cost. On the other hand, silicon provides two severe inconvenients: firstly, it produces high contraction of the part, putting in risk the part’s dimensional tolerance. Secondly, its affinity with oxygen promotes the formation of oxides during sintering.

Added to master alloys, like Mn, provides an improvement in mechanical properties at the expense of oxide formation. The master alloy composition and the sintering atmosphere are two key factors to avoid any oxide formation that could be harmful to the development and properties of the component (12).

6.4.7. Mo

Molybdenum improves the hardenability, toughness and tensile strength of steel. It increases the hardenability by lowering the required quench rate during the heat-treating process. Molybdenum is also used to improve corrosion resistance of steel by reducing the risk of pitting, as it improves resistance to Cl^- induced corrosion.

7. MATERIALS

7.1. STARTING MATERIALS

In this project several materials have been employed in powder form to fabricate the specimens to study the master alloys behaviour. Their characteristics are shown in Table 1

Table 1 Characteristics of powders employed to obtain the mixes

Base powder	Nomenclature	Manufacturer	Characteristics
Fe-0,85Mo powder	Astaloy 85Mo	Höganas AB	Fe and Mo powder water atomized >150 µm 23,1% <150 µm & >45 µm 61,7% <45 µm 23,1% $\rho_{apparent}$: 3,08 g/cm^3
Master Alloys	MA1	AMES	Fe-36,5Mn-4,5C O: 0,08% wt C. 4,49% wt $Ø_{particle}$= variable T melting: 1100ºC

	MA2	Universidad Carlos III de Madrid	Fe-36,5Mn-6C O: 0,08% wt C: 6,00% wt $Ø_{particle}$= variable
	MA3		Fe-35Mn-12Si-10Cr O: 0,08% wt O: 0,08% wt $Ø_{particle}$= variable T melting: 1150ºC
	MA4		Fe-40Mn-15Si-3Ni O: 0,08% wt O: 0,08% wt $Ø_{particle}$= variable T melting: 1120ºC
Graphite	M3 Graphite	IMERYS Graphite & Carbon	Natural graphite
Wax	Wax	Münzing Microtech	Synthetic wax (bis-amide)

The master alloys employed were previously designed in AMES with the use of thermodynamic calculations and produced on demand by Universidad Carlos III de Madrid.

The first master alloy (MA1) is an alloy that is already used in the production of parts and has shown to be a good addition to the production catalogue. This has been incorporated into the study for two reasons: to study in more depth its behaviour during sintering and, also, to be used as a reference point to compare it with the other three alloys.

MA2 is a version of the MA1 with more carbon. This is used to introduce more carbon to the part to increase its mechanical properties without adding carbon to the Fe+MA mixture. This is done to verify if there really is any difference between adding carbon externally or adding it to the master alloy.

MA3 and MA4 were designed with two objectives: on the one hand, introduce Mn and Si as the main alloy elements of steel during sintering. On the other hand, obtain a melting temperature close to that of the sintering temperature, so that a transient liquid phase can be obtained during sintering and thus favour the distribution of alloy elements. For the design of these master alloys the *Thermocalc* software was used, which allows the design of metallic alloys phase diagrams with the set objectives thanks to the use of thermodynamic calculations and simulations. In MA3, Cr was added and in MA4, Ni was added. These elements contribute to the thermal stability of the master alloy and provide an improvement in the properties of the manufactured parts.

All master alloys were produced by atomization and the particle size for the study has been set to a maximum of 45 µm except for MA1, where the maximum particle size is 25 µm since the supplier manufactures the powder according to these specifications. The particle size in the other master alloys has not been matched to the one of the MA1 because the performance of the atomization on demand is not sufficient to discard so much material. In an industrial process specifically designed for a said type of alloy it is possible to set this maximum size to 25 µm.

The rest of the materials used are typical powders used in the production of parts at AMES. Fe is the main material used in the manufacturing of specimens. Graphite is used to level the carbon content in all mixtures and the wax is used as a lubricant during pressing so as not to damage the pressing die.

7.2. MIXES AND COMPOSITIONS

For this project twelve compositions are selected. These combine all the different master alloys with different quantities of carbon. The mixes are made with a base of Astaloy-85Mo, a fixed quantity of master alloy (4% wt.) with a fixed particle size of 45 $Ø_{partícle}$<45 µm and three different levels of C, ranging from 0,2% to 0,8% in weight. In all mixes the level of lubricant is fixed at 0,6% in weight. Compositions and nomenclatures are shown in Table 2 (0,6% wax is added to 100% total mix, this means that the composition levels are calculated from 100,6% of mix).

Table 2 Mix compositions with master alloy

Mix composition	Nomenclature	Steel composition
Fe-0,85Mo 4% MA 0,6% Wax 0,2% C	2M	Fe-(0,8-1)Mo-0,2C
	2M1	Fe-(0,8-1)Mo-(1-1,6)Mn-0,2C
	2M2	Fe-(0,8-1)Mo-(1-1,6)Mn-0,2C
	2M3	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,6)Si-(0,3-0,6)Cr-0,2C
	2M4	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,7)Si-(0,1-0,2)Ni-0,2C
Fe-85Mo 4% MA 0,6% Wax 0,5% C	5M	Fe-(0,8-1)Mo-0,5C
	5M1	Fe-(0,8-1)Mo-(1-1,6)Mn-0,5C
	5M2	Fe-(0,8-1)Mo-(1-1,6)Mn-0,5C

	5M3	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,6)Si-(0,3-0,6)Cr-0,5C
	5M4	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,7)Si-(0,1-0,2)Ni-0,5C
Fe-85Mo 4% MA 0,6% Wax 0,8% C	8M	Fe-(0,8-1)Mo-0,8C
	8M1	Fe-(0,8-1)Mo-(1-1,6)Mn-0,8C
	8M2	Fe-(0,8-1)Mo-(1-1,6)Mn-0,8C
	8M3	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,6)Si-(0,3-0,6)Cr-0,8C
	8M4	Fe-(0,8-1)Mo-(1-1,6)Mn-(0,3-0,7)Si-(0,1-0,2)Ni-0,8C

8. EXPERIMENTAL PROCESS

The experimental process that takes place to develop this study and obtain the necessary data can be divided in four different phases:

Mixing

Firstly, all the materials are mixed to obtain the desired composition in a homogeneous mix that will be used for the testing.

Pressing

The second phase is the pressing of all the specimens needed for the selected tests using the mixes obtained in the first phase.

Sintering and thermal treatment

All the specimens are sintered under the selected conditions. In this case, only known industrial conditions will be applied. Afterwards, those specimens that are selected, will be treated with a thermal treatment.

Characterization

Lastly, the characterization phase encompasses every single testing needed in order to obtain all the necessary data and discuss the results to come up with conclusions. Mechanical, chemical, dimensional and optical testing are conducted.

8.1. MIXING

In the mixing phase all the different powders are combined to produce the desired mixes stated in the chapter above. The process is done in a bicone mixer for 20 minutes and the result is a homogeneous mix.

8.2. COMPACTING

To obtain the green specimens the mixes are pressed in different morphologies depending on the test that has to be carried out.

This process is done in an automatic press developed by AMES-CMA for the AMES' laboratory pilot plant. This press has an automatic powder charger that ensures the right amount of powder is used each cycle and a hydraulic system controls all parameters.

A density of 7g/cm^3 is set as the default for every specimen independently of their morphology, this makes sure that all specimens have the same initial conditions.

There are two different morphologies prepared for this project:

Tensile Strength Test (Figure 4): These parts are prepared in accordance with the ASTM E8-16a norm (13). Their complex morphology only lets us use these for tensile strength testing and hardness testing.

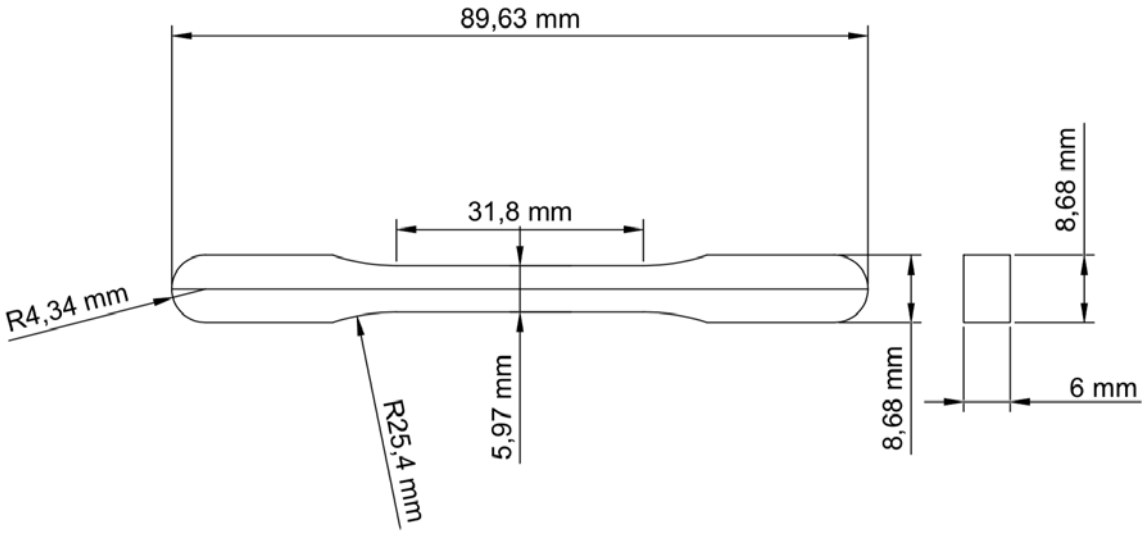

Figure 4 Tensile strength testing specimen specifications

Charpy Impact Test (Figure 5): The parts for this test are prepared in accordance with the ASTM E23-07a norm (14). The simple morphology of these specimens also lets us use them as a way to measure dimensional variation, hardness, density changes and the influence of thermal treatment throughout the whole part.

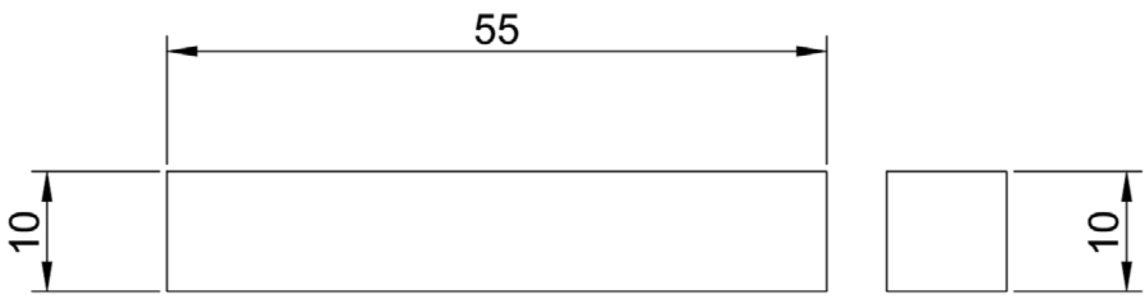

Figure 5 Charpy impact testing specimen specifications

All the measuring is carried out after the pressing to observe the effects of sintering conditions.

8.3. Industrial sintering and thermal treatment

In previous investigations step sintering cycles were performed, therefore in this project only industrial sintering is carried out. The conditions of atmosphere and temperature are the ones most usually employed when producing commercial parts. This will provide results comparable to those of normal steel components and will give a better insight on the viability of master alloys in an actual industrial environment.

Industrial furnaces work at different temperatures and atmospheres depending on the type of component that is being produced on that moment, this is why certain conditions are much harder to be carried out, such as 100% hydrogen atmosphere sintering, for example. For this study, three conditions are selected (Table 3), which will give information about the differences caused by different temperatures, velocities and atmospheres.

Table 3 Sintering conditions

Sintering	Temperature	Velocity	Atmosphere
Common sintering conditions at AMES	1120ºC	Belt 10 m/h	90% N – 10% H
High temperature sintering to help diffusion mechanisms	1180ºC	Belt 10 m/h	90% N – 10% H

High temperature in pure hydrogen to ensure master alloy melting and oxide reduction	1180ºC	Steps 300s/step	100% H

All of the sintering processes are carried out in industrial sintering furnaces. These work using a belt system to carry the parts through different sections. These can include different sections such as a binder removing section, preheat section, low or high temp sections, etc. There are also high temperature sintering furnaces which use a step system to move the parts throughout the whole heating chamber.

Thermal treatments are also carried out to decide whether a secondary process is beneficial for the mechanical properties of the master alloy. The following thermal treatments are some of the most common at AMES used for commercial parts ():

Table 4 Thermal treatments

Thermal Treatment	Temperature	Time
None	-	-
Carbonitriding	860ºC	15’
Case-hardening	860ºC	15’

8.4. CHARACTERIZATION

8.4.1. Dimensional analysis

Dimensional analysis gives an insight about the volume, weight and density changes after the sintering phase takes place. All the specimens are measured and weighted before and after sintering. Dimensions are measured with a micrometre and weight is measured using a laboratory scale.

The results of this analysis give information about the changes suffered during the sintering phase, such as dilation, compression, material loss, etc. Density also can be related to the porosity of the material.

8.4.2. Mechanical analysis

Through mechanical analysis a characterization of the mechanical properties can be obtained. There are several mechanical tests that can be performed to determine all the different properties of a material. For this project, tensile strength and resilience tests are carried out.

The tensile strength test is performed with a universal test machine (model Shimadzu AG-IS) that measures the required tension to break a specimen. The software included with the machine then applies the necessary calculations to draw a tension/deformation graph and gives out the ultimate tensile strength of the material. The yield strength and the elastic limit of the material can also be calculated with the help of an extensometer.

The Charpy test is used to calculate the energy absorbed when the material is impacted with a pendulum. This is used to calculate the resilience of the material (in J/cm^2) as shown in the equation below (Equation 1). The pendulum used is a *Hoytom* model. The results are obtained using the gravity's acceleration (g) and the dimensions of the specimen (b and h) from the obtained value (C).

$$Resilience = \frac{C \cdot g}{b \cdot h} \cdot 100$$

Equation 1 Resilience through Charpy's pendulum test

The hardness values are obtained with a *Hoytom* hardness meter. Since the hardness values vary from one mix to another, different hardness scales are used, from Rockwell A to Rockwell C. Since some thermal treatment might affect the hardness values of the surface of the material, different hardness values are measured for each zone of the specimen.

8.4.3. Chemical analysis

Chemical analysis provides information about the chemical composition of the final specimens. The main objective of the tests carried out, are to control that the carbon, sulphur or oxygen values are found within the expected ranges previously calculated.

To perform these tests two test machines from *Leco* are used. Carbon and sulphur concentrations are measured with the CS-200 model, while oxygen and nitrogen levels are measured with the EF-400 model.

To observe the composition evolution for several temperatures and conditions, SEM/EDS analysis are carried out with a Zeiss EVO MA25 SEM paired with a Bruker EDX Spectrometer.

8.4.4. Optical analysis

An optical analysis reveals information about the material's structure, its development rate, sintering neck formation, the master alloy particle state and the carbon's evolution throughout the whole part. This analysis also provides information about the interior of the master alloy particles and the changes that take places during the sintering phase.

To perform this analysis, metallographic specimens must be prepared. To make these the metal is cut with a linear precision saw (model Buehler IsoMet 5000); after that, with a mounting press, the metal specimen is mounted in resin to make the polishing easier and even. The metal is then grinded and polished with a Buehler MetaServ 250 automatic polisher.

Once the metal is polished, the specimen is attacked with an etchant, mostly acid and other reagents (in the case of conventional steel, natal is used). Once the specimen is polished and etched, it is ready for optical analysis.

8.4.5. Optical microscope

Etched specimens are observed with an Olympus reverse-optical microscope, where specimens can be observed at up to 100x. The specimens are usually observed at 10-20x to get an overview of the microstructure like in Figure 7, and then at 50x-100x if more detail is needed, like in Figure 7.

Figure 7 20x micrography where an overview of the microstructure can be observed

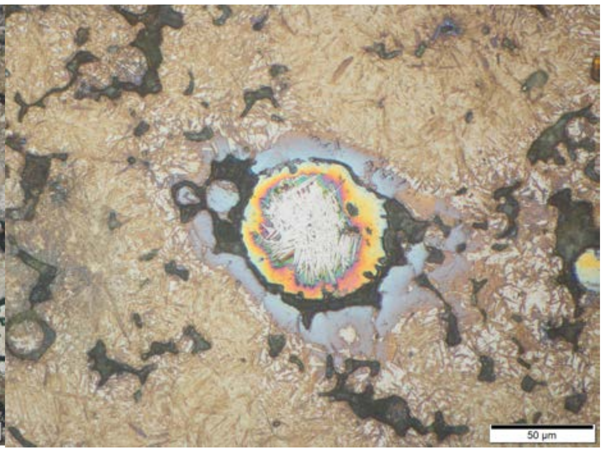

Figure 7 50x micrography, where a master alloy particle can be observed in further detail

8.4.6. SEM

When further information about the material's composition is needed, the part is introduced into a scanning electron microscope (model Zeiss MA-25). This enables the user to take pictures in more detail and get basic information about the material's composition. An example of the results given by the SEM analysis are shown in Figure 8.

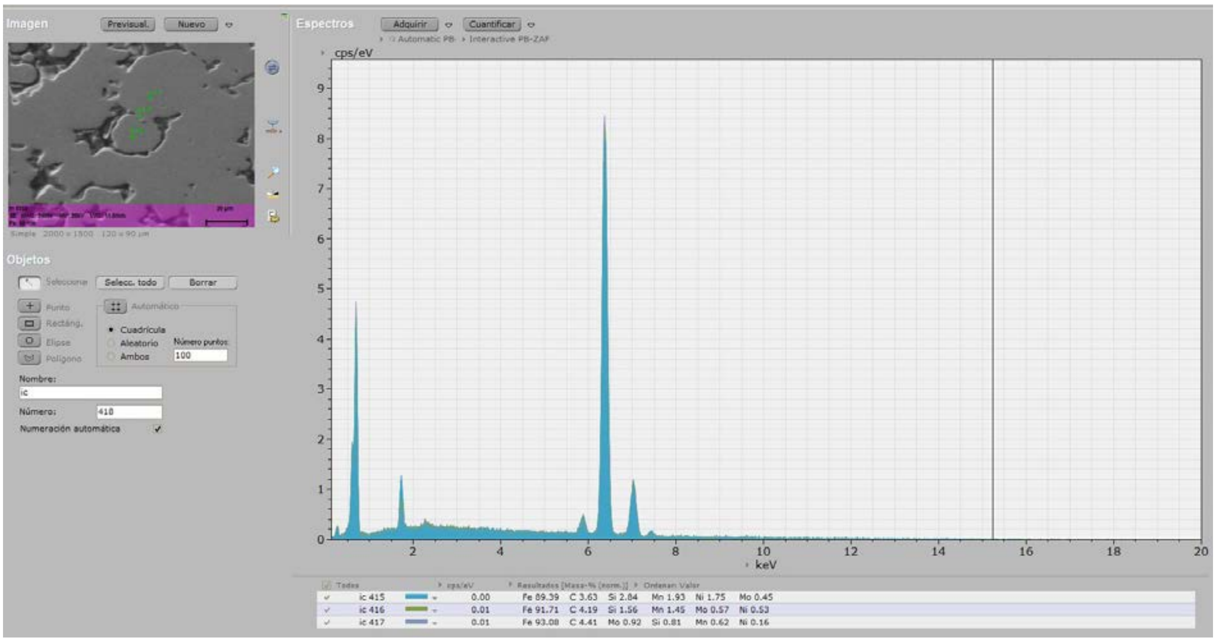

Figure 8 SEM results; composition and detail of a master alloy particle

9. RESULTS AND DISCUSSION

Taking into account all the different variations of sintering temperatures, thermal treatments and mixes stated in the previous chapters, there is a good number of specimens with many different combinations of conditions. An overview of all the different conditions is shown in the table below (Table 5):

Table 5 Every combination of properties for the designed steels

<table>
<tr><th>Base</th><th>MA</th><th>C (%)</th><th>T (ºC)</th><th>TT</th></tr>
<tr><td rowspan="4">Astaloy 85Mo</td><td>FeMn-4.5C</td><td>0</td><td rowspan="2">1120</td><td rowspan="2">Carbonitriding</td></tr>
<tr><td>FeMn-6C</td><td>0,2</td></tr>
<tr><td>FeMnCrSi</td><td>0,5</td><td rowspan="2">1180</td><td rowspan="2">Case-hardening</td></tr>
<tr><td>FeMnSiNi</td><td>0,8</td></tr>
</table>

The nomenclature given to the specimens follow the set of rules stated in the figure below (Figure 9):

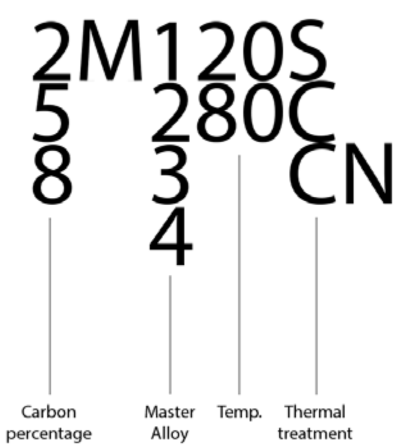

Figure 9 Nomenclature of the specimens

The first number shows the available carbon percentages, ranging from 0,2% to 0,8%. The letter M stands for Master Alloy, it remains invariable in this study. The second number stands for the Master Alloy used, as stated in Table 1. The third and fourth number is the temperature, where 20 is 1120ºC and 80 is 1180ºC. The last letter(s) is the thermal treatment applied; S for non-treated specimens, C for case-hardening and CN for carbonitriding.

The different testing methods and analysis carried out allow the characterization of the different sintering phenomena that take place at different temperatures and conditions, which is of great use to construct a map of the microstructural evolution of the different systems. While a complete metallurgic characterization is impossible due to the great amount of work and time it would take, some of the basics of the microstructural evolution are discussed to better understand the results obtained in the mechanical testing.

9.1. MECHANICAL AND PHYSICAL PROPERTIES

9.1.1. Dimensional variation

The contraction and expansion of the specimens is a critical aspect in sintering due to the nature of the process itself; a process where dimensional accuracy and finish of the components are one of their main strengths.

To measure these changes with maximum accuracy, the length of the Charpy impact test specimen is measured before and after sintering. Being this the largest dimension measurable, minimum human error is ensured when calculating the dimensional change.

The dimensional variation for the different specimens is shown in the graphs below (Figure 10).

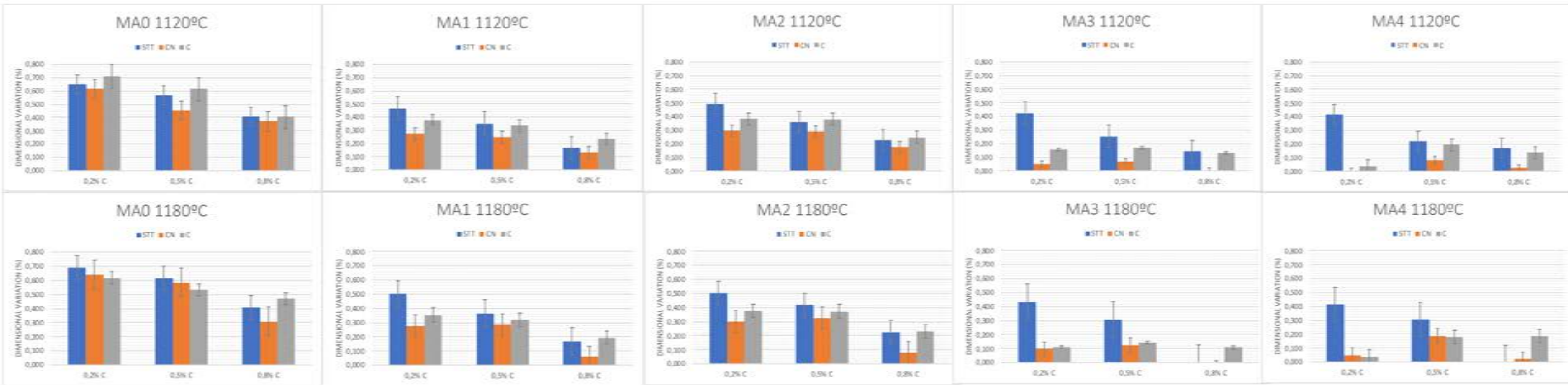

Figure 10 Dimensional variation of every specimen

As seen in the results above, none of the specimens has a dimensional variation above 0,7%, and their deviation is usually found in the 0,1% realm. This indicates that the dimensional variation is predictable and controllable for all of the given master alloy mixes.

It is also very clear the influence of carbon content and different alloying elements to the dimensional variation. An increase in the carbon content decreases dimensional changes due to the tendency of carbon at diffusing interstitially inside Fe, reinforcing iron's crystal lattice and hindering atom movement, therefore reducing these dimensional changes. The addition of other alloying elements such as Si, Ni or Cr also present a decrease in dimensional variation; again, the addition of stranger atoms inside the Fe crystal lattice (this time atom substitution instead of atom interstition due to a larger atomic radius) hinders dimensional changes. Lastly, carbonitriding and case-hardening thermal treatments also result in a decrease in dimensional variation, probably caused by the carbon concentration increase in the surface of the specimen with the exposure of carbon-containing atmospheres.

9.1.2. Density

The density of the specimens is calculated with the Charpy impact specimens like the dimensional variation. The simplicity of their morphology eases substantially the calculations and speeds up data gathering. The results are shown in the graphics below (Figure 11). The green specimens are pressed in order to obtain a density of 7g/cm^3 for every specimen before sintering. Usually, the expected result is a gentle increase in density.

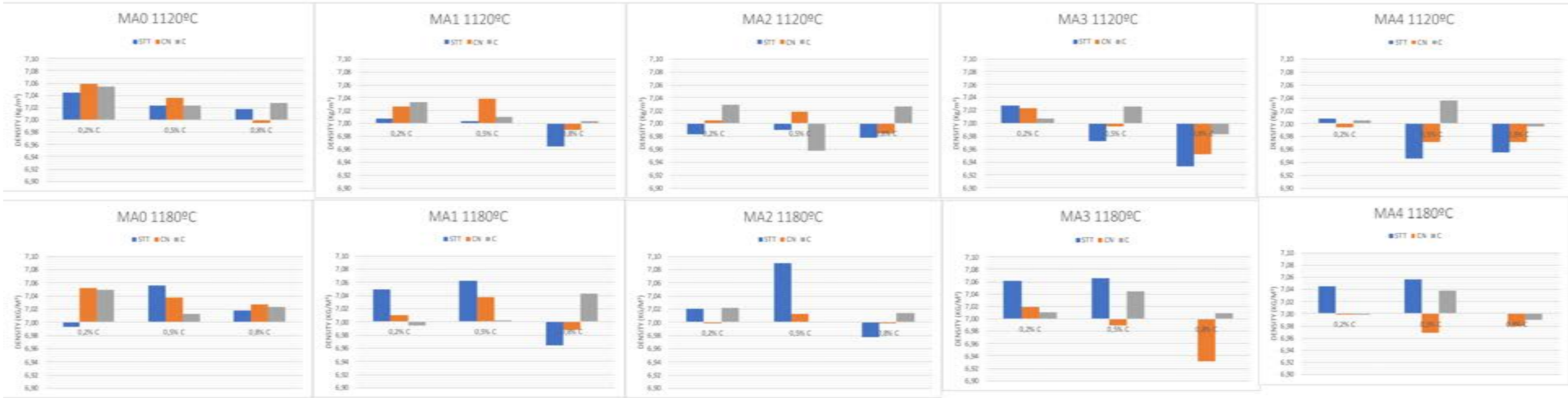

Figure 11 Density of every specimen

The density of the specimens in this case does not present clear results; this might be due to the inconsistency of the press during the fabrication of the specimens. Even though the goal is to obtain a density of 7g/cm^3, the press has not been able to perform consistently to give the desired results. While this is not ideal, the densities obtained do not deviate more than 1-2% of the original density, which make these results non-worrying, yet unusable to obtain conclusions. Further adaptations of the master alloys for industrial processes will focus more on this matter.

9.1.3. Ultimate tensile strength

Tensile strength testing provides a way to obtain several mechanical properties of a material. Measuring the strength that a material requires to break, gives the ultimate tensile strength of the material. This combined with an extensometer also allows to obtain a material's elastic limit and young's modulus. For this case, only the ultimate tensile strength value is sufficiently reliable to extract any clear conclusions; the high hardness obtained (which will be discussed afterwards) on some of the parts makes some of them slip off the clamps of the universal test machine and the extensometer's gripper. An image of the resulting part when slipping occurs is shown below (Figure 12).

Figure 12 Tearing due to slipping off the testing machine's clamp

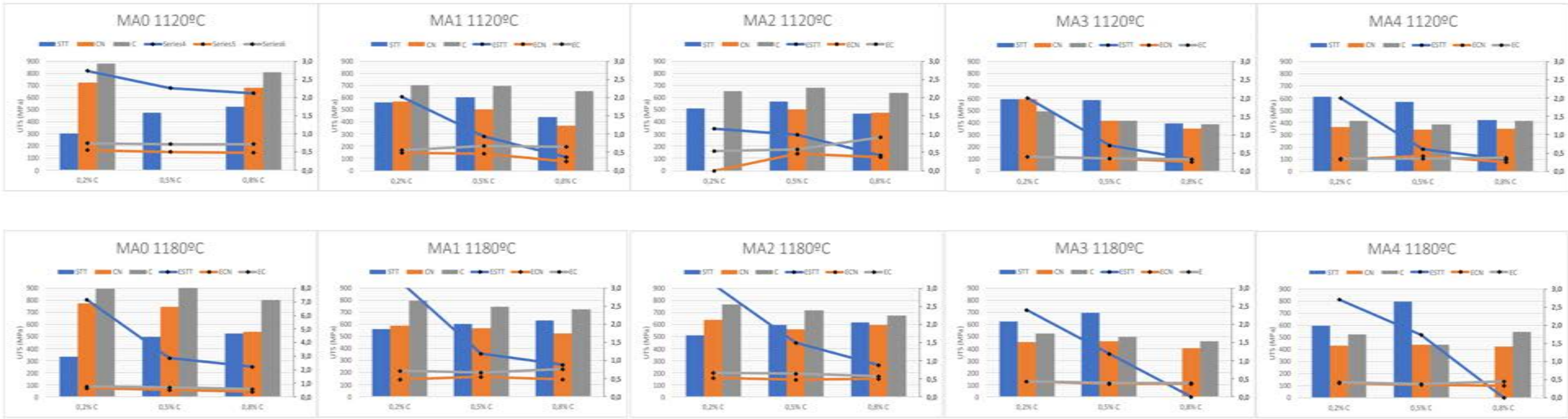

Figure 13 UTS and elongation of every specimen

The graphics shown above (Figure 13) are all the results of the ultimate tensile strength testing of the specimens. The two missing results are caused by the slipping of the parts discussed above.

For the non-master alloy steel specimens, it is clear that a substantial improvement to the tensile strength is achieved when a thermal treatment is applied. This change is caused due to the thermal treatment temperature (860ºC) reaching temperatures higher to those of recrystallization of steels, compromised between 400-700ºC. Reaching temperatures above recrystallization helps the grain size grow, improving mechanical properties such as tensile strength and reducing hardness at the same time, even though that last one is also improved, which will be discussed later.

While not reaching the same tensile strength, a tendency where thermal treatment no longer provides an improvement is observed. As predicted, high temperature sintering presents better overall results, and the addition of elements such as Ni or Cr makes it so thermal treatment is no longer suitable for the improvement of the sintered components, meaning that comparable mechanical properties to those of treated steel are achievable without the need of secondary processes. In the case of MA1 and MA2, thermal treatment remains suitable for improving mechanical properties, but untreated steel presents a substantial improvement.

The general tendency for all specimens is that the addition of master alloys to the mixture improves mechanical properties without the need of further thermal treatments, reducing the overall cost of the component.

9.1.4. Charpy impact toughness

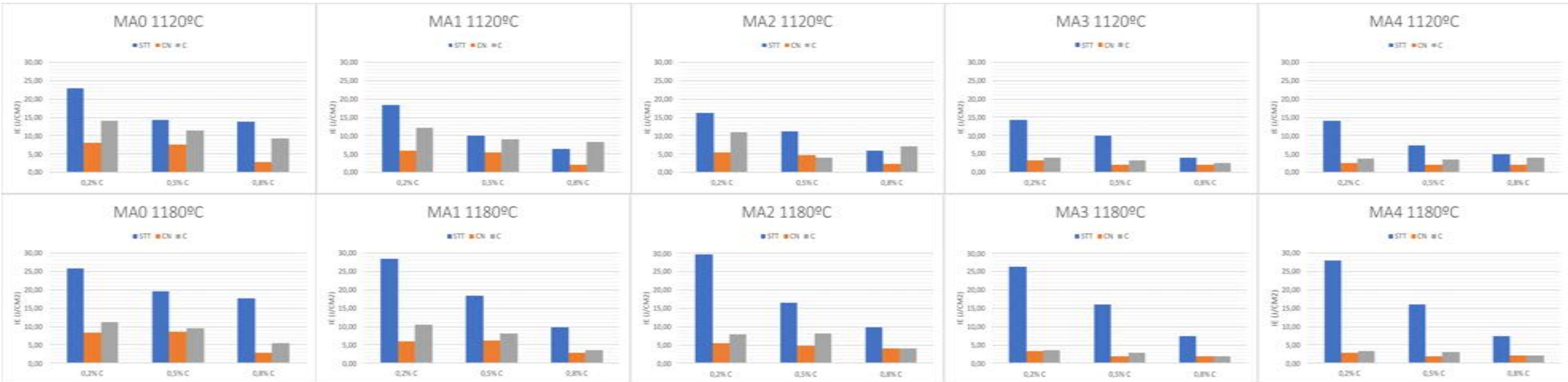

Figure 14 Charpy impact test results of every specimen

When looking at the charpy test results (Figure 14), it is obvious that an increase in the carbon content, whether that is through the addition of it through the master alloy or the addition of it through thermal treatments, generates an embrittlement of the part, worsening energy absorption at impact. This is an expected result and the constant results throughout all the specimens are a good indicative. There is even a slight improvement in every non-treated specimen over the MA0 specimen for the 1180ºC case.

Adding to the carbon content, the sintering temperature also plays an important role when obtaining higher resilience values. As stated above, there is an improvement over the specimen without any master alloy for the 1180ºC case, evincing the importance of temperature during the sintering phase, even if the increase is as slight as 60ºC.

9.1.5. Hardness

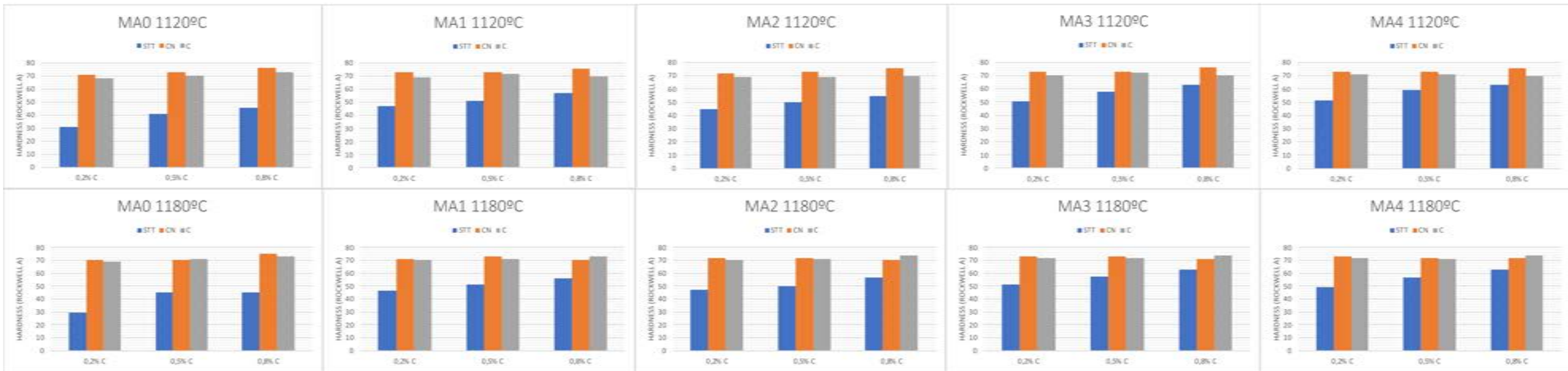

Figure 15 Hardness values of every specimen

The values shown in the figure above (Figure 15) show the hardness levels of every single specimen's surface. All the values are represented in the Rockwell A scale; this is not ideal and higher values should be represented in a more fitting scale (they were measured with Rockwell C scale), but for the sole sake of comparison, they are represented in the Rockwell A scale. Actual values in the Rockwell C scale can be found in the appendices section.

The hardness values for thermal treated parts all remain almost identical. This is due to the carbon content present in the surface of the specimens, deposited during the thermal treatment phase. For the non-treated specimens, an increase in the hardness levels is observed for all the master alloys. This increase translates into a higher wear resistance and therefore higher service life and resistance to other wearing factors such as corrosion.

9.2. MICROSTRUCTURAL EVOLUTION

The microstructure of a metallic specimen can give out a great amount of information about the part itself, enabling the prediction of certain behaviours and properties of the part.

For this project, and for the sake of keeping it brief, only certain microstructures are compared. There are two factors to be compared: carbon content and sintering temperature. For this reason, only 1180ºC (0,2; 0,5 & 0,8%C) and 1120ºC 0,8%C, are compared between each other.

	Master alloy particle		Sintering neck		Fe matrix

%wt	1180 S/TT														
	2M			2M1			2M2			2M3			2M4		
Fe	96,76	96,75	96,22	89,20	93,92	95,45	83,18	93,30	94,60	93,90	93,93	94,29	87,08	90,33	90,42
C	2,58	2,55	2,87	3,56	3,26	2,70	2,96	2,94	3,52	2,31	2,82	3,04	5,84	5,91	5,80
Mo	0,66	0,70	0,91	0,42	0,36	0,57	0,16	0,44	0,61	0,63	0,53	0,61	0,13	0,20	0,64
Mn	-	-	-	6,82	2,45	1,28	13,70	3,31	1,27	0,96	0,90	0,97	1,91	1,39	1,70
Si	-	-	-	-	-	-	-	-	-	0,89	0,77	0,55	1,35	1,09	1,02
Cr	-	-	-	-	-	-	-	-	-	1,32	1,04	0,54	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	3,68	1,07	0,42

%wt	1180 S/TT														
	5M			5M1			5M2			5M3			5M4		
Fe	96,33	94,39	96,56	92,32	93,58	93,58	90,20	91,97	93,52	91,88	91,13	93,57	89,39	91,71	93,00
C	3,01	5,02	2,86	4,16	4,36	4,62	3,63	3,55	4,48	3,36	4,72	3,87	3,63	4,19	4,41
Mo	0,66	0,58	0,58	0,70	0,73	0,47	0,13	0,43	0,67	0,37	0,63	0,55	0,45	0,57	0,62
Mn	-	-	-	2,83	1,34	1,33	6,04	4,05	1,33	1,37	1,11	1,23	1,93	1,45	0,62
Si	-	-	-	-	-	-	-	-	-	1,04	1,06	0,31	2,84	1,56	0,81
Cr	-	-	-	-	-	-	-	-	-	1,98	1,35	0,46	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	1,75	0,53	0,16

%wt	1180 S/TT														
	8M			8M1			8M2			8M3			8M4		
Fe	99,20	98,95	99,25	92,95	94,20	94,62	98,04	98,21	97,73	90,67	93,69	97,66	95,32	95,16	97,45
C	-	-	-	3,48	3,91	3,56	-	-	-	-	-	-	-	-	-
Mo	0,80	1,05	0,75	0,58	0,45	1,00	0,63	0,83	0,75	-	-	0,86	0,53	0,79	0,72
Mn	-	-	-	2,99	1,43	0,81	1,24	0,86	1,48	1,72	1,30	1,05	0,86	1,65	1,34
Si	-	-	-	-	-	-	0,09	0,10	0,04	2,68	2,23	0,14	2,00	1,89	0,40
Cr	-	-	-	-	-	-	-	-	-	4,94	2,79	0,29	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	1,29	0,51	0,09

% wt	1120 S/TT														
	8M			8M1			8M2			8M3			8M4		
Fe	94,02	96,03	96,23	91,75	92,98	94,87	83,22	93,70	94,49	81,77	88,57	93,90	97,62	97,58	98,99
C	5,34	3,34	3,14	3,17	3,79	3,11	3,13	2,83	3,97	4,31	3,53	3,40	-	-	-
Mo	0,64	0,63	0,63	0,42	0,47	0,66	0,46	2,93	0,93	0,55	0,51	0,77	0,76	1,17	0,80
Mn	-	-	-	4,65	2,76	1,36	13,19	0,54	0,61	2,56	2,01	1,06	1,30	0,80	0,08
Si	-	-	-	-	-	-	-	-	-	4,58	2,70	0,29	0,33	0,45	0,13
Cr	-	-	-	-	-	-	-	-	-	6,23	2,68	0,58	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Figure 16 Specimens composition

The figure above (Figure 16) shows the elemental composition for three different zones: master alloy particle, sintering neck and Fe matrix. In Figure 17 an example of these three different zones are shown:

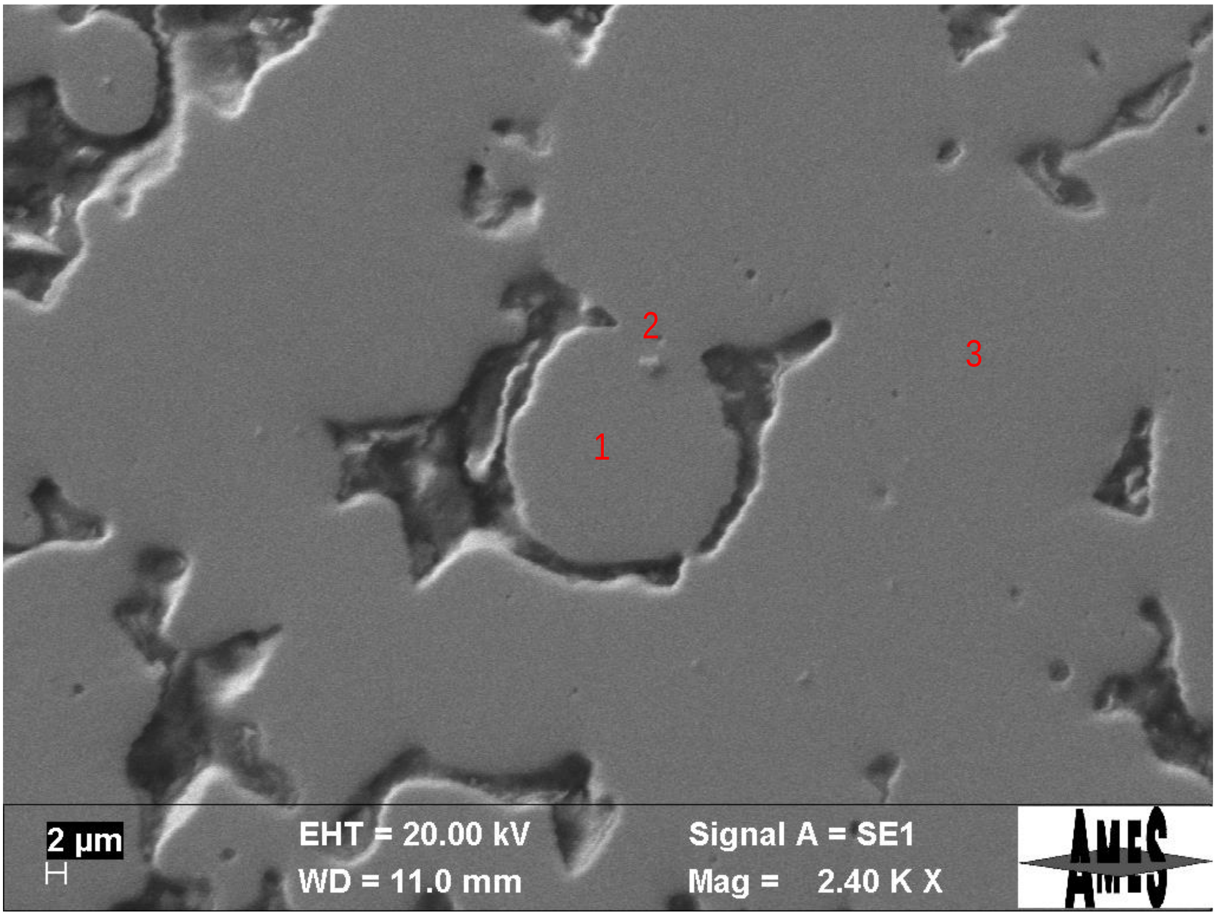

Figure 17 Master alloy particle as analysed with EDS

Zone 1 is the interior of the master alloy particle; zone 2 is the sintering neck formed between the master alloy particle and the Fe matrix; and zone 3 is the base Fe matrix.

9.2.1. Influence of carbon content

Carbon can be added in two different ways: inside the master alloy during the atomization or adding it during the mixture preparation as spheroidal graphite.

The concentration of graphite affects the diffusion of other elements. Based on Figure 17, carbon added into the master alloy keeps the Mn enclosed in it, and the master alloy particle keeps a nearly round shape (Figure 18), meaning only a little loss of matter occurs. In specimens with less carbon, the master alloy has a more irregular shape and a wider space between the master alloy particle (Figure 19), but the Mn content in the matrix indicates that no Mn has diffused into the matrix. In previous studies this is associated with the sublimation of Mn, which has a lower boiling temperature (9).

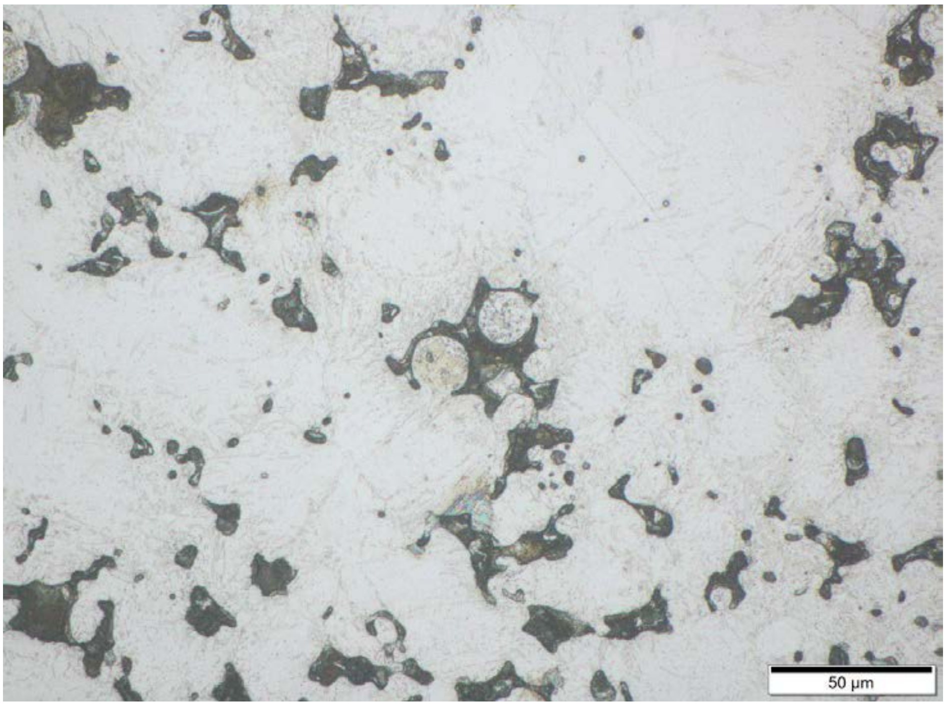

Figure 18 Specimen with high carbon content inside the master alloy

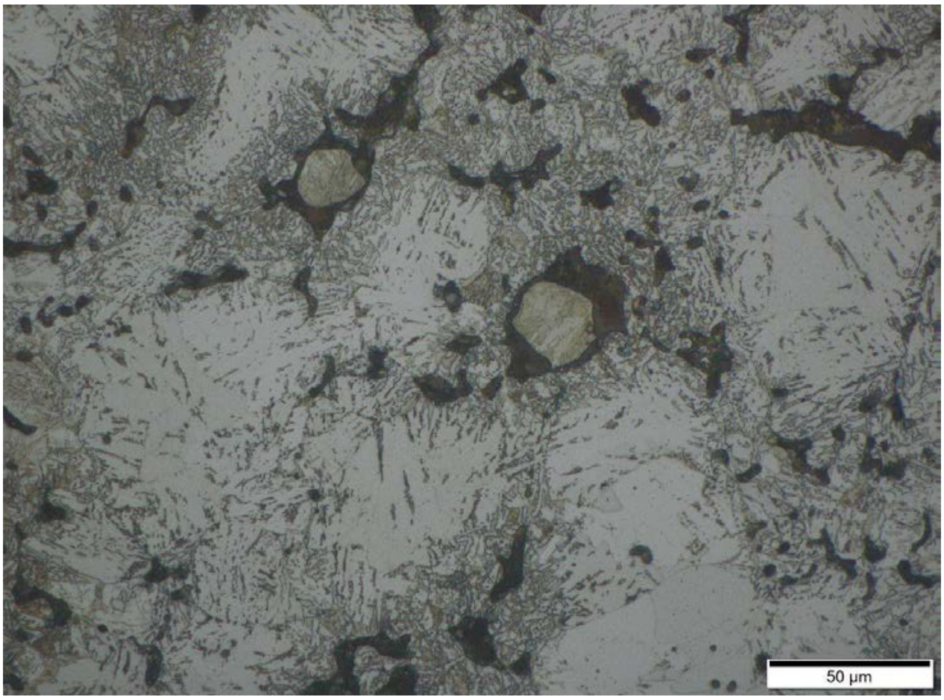

Figure 19 Specimen with low carbon content inside the master alloy particle

Also, as seen in the figures above, a lower carbon content in the master alloy particle translates into a kind of halo around the master alloy particle, with a rich Mn content.

When adding carbon into the Fe matrix, the carbon hinders the Mn diffusion into the matrix lowering again the Mn content in the Fe matrix.

As a little recap, carbon content hinders Mn diffusion in general, whether that is when letting the Mn exit the master alloy to diffuse into the Fe matrix, or when letting the Mn enter the Fe matrix.

This effect is not only observed with Mn alone; the diffusion of other elements such as Ni, Si or Cr is heavily reduced with a higher carbon content in the Fe matrix. The same happens with diffusion of Mo into the master alloy particle.

This effect of carbon is presented as an interesting mechanism; the previously designed liquid phase is not forming in low carbon specimens due to the beforementioned sublimation of Mn, increasing the melting temperature of the master alloy to temperatures higher than sintering ones. If Mn sublimation can be controlled with carbon content and introduction, a liquid phase may be viable during the sintering phase. This is the case with higher temperature sintering in high carbon specimens, where a liquid phase can be observed.

9.2.2. Influence of temperature

Temperature is one of the main aspects of the sintering process. High temperature sintering at 1180ºC occurs at a higher temperature than the melting point of the master alloy. Low carbon specimens and high carbon specimens present broader differences at that temperature. On one hand, low carbon specimens remain with an irregular shape and a greater space between the master alloy and the matrix, indicating that sublimation of Mn keeps taking place, and that when Mn condenses on the master alloy particle, forms an oxide layer which keeps other elements from diffusing into the matrix. On the other, specimens with high carbon concentration present a much smoother Mn concentration gradient and a master alloy particle with less space between particle and matrix, as well as sintering necks. This is caused by the formation of a transient liquid phase due to the partial fusion of the master alloy particles in the higher carbon mixtures; this fusion helps to the formation of sintering necks and gives a rounder shape to the master alloy and pores (Figure 20).

Overall, these microstructural changes give better mechanical properties as seen in the previous chapter. With the SEM analysis a better distribution of the alloying elements is observed, confirming the hypothesis of the transient liquid phase.

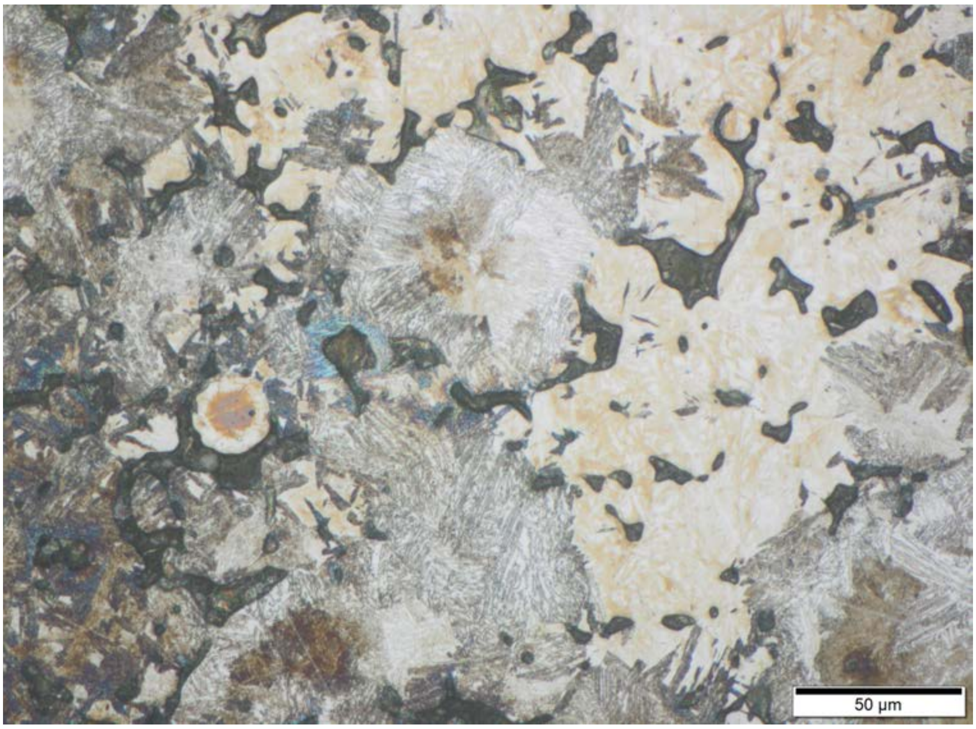

Figure 20 High carbon specimen (8M2) sintered at 1180ºC

10. CONCLUSIONS

This project enriches the knowledge about the sintering of steels with high oxygen affinity elements introduced as master alloys.

The main conclusions are presented in the following lines:

- The most important mechanism and the one that determines most of the mechanical properties obtained is Mn behaviour at sintering temperatures and its interaction with other elements such as carbon or oxygen, which condition the master alloy particles behaviour.
- Mn starts sublimation at about 800ºC (9), which changes the master alloy's composition continuously, provoking a quick decrease in Mn concentration. This Mn condensates on the master alloy particles and forms an oxide layer which hinders further diffusion of elements into the Fe matrix, as well as sintering necks formation.
- Carbon has a great effect in the aforementioned mechanisms and hinders Mn sublimation, keeping master alloy particles composition constant, improving neck formation and reducing oxide formation.
- Carbon added in the mixture also helps reducing formed oxides during the sintering phase (3), and therefore improving mechanical properties.
- Master alloy particles do not melt at the temperature they were designed to, caused by the Mn sublimation. This has several implications, such as slower diffusion of other elements to the point where they are rendered almost useless. This phenomenon makes it so sintering at 1120ºC hinders severely the formation of sintering necks and diffusion. Higher temperature sintering provides better results, propitiated by the better diffusion and sintering necks formation, due to the reduction of oxides assisted by carbon and the partial fusion of master alloy particles which eases element transit between master alloy and matrix.

- Mechanical properties obtained through high temperature sintering without thermal treatment are comparable to those of commercial steels. Mn and Si addition as a master alloy can be a viable process for the production of sintered steels.

These conclusions provide a better insight on the mechanisms of sintering in the presence of Mn and Si included as a master alloy and will prove useful in future investigations with the purpose of developing new master alloy systems at an industrial level.

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APPENDICES

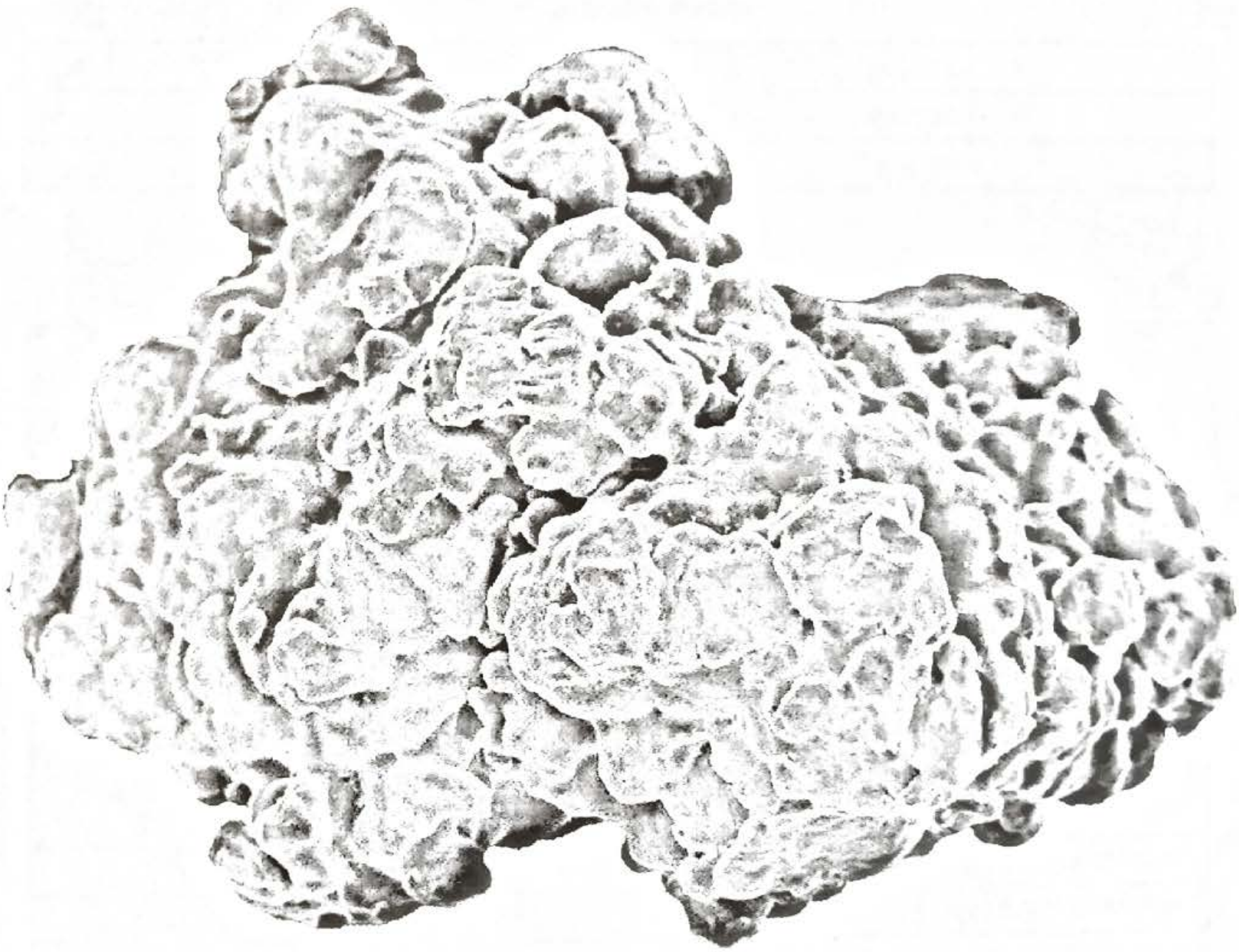
APPENDIX 1: PROPERTIES FOR ALL GIVEN SPECIMENS

			1120 1NC 10m/h							
			Propietats generals			UTS			Charpy	
			Longitud sinter. (mm)	Densitat sinter. (g/cm^3)	Var.Dim. (%) [Shrinkage]	UTS (MPa)	ε (%)	Duresa	IE (J/cm^2)	Hv superfície
0,2% C	CN	2M	54,663	7,06	0,61	725	0,549	41 HRC	8,00	41 HRC
		2M1	54,849	7,03	0,27	570	0,479	43 HRC	6,00	43 HRC
		2M2	54,836	7,01	0,30			43 HRC	5,53	43 HRC
		2M3	54,972	7,02	0,05	594	0,395	45 HRC	3,24	45 HRC
		2M4	55,002	7,00	0,00	360	0,314	45 HRC	2,61	45 HRC
	C	2M	54,610	7,05	0,71	880	0,735	36 HRC	13,96	36 HRC
		2M1	54,791	7,03	0,38	705	0,551	37 HRC	12,11	37 HRC
		2M2	54,789	7,03	0,38	654	0,543	38 HRC	10,84	38 HRC
		2M3	54,913	7,01	0,16	495	0,395	40 HRC	4,00	40 HRC
		2M4	54,978	7,01	0,04	417	0,345	41 HRC	3,77	41 HRC
	S/TT	2M	54,642	7,05	0,65	306	2,719	31 HRA	22,86	31 HRA
		2M1	54,743	7,01	0,47	559	2,013	47 HRA	18,25	47 HRA
		2M2	54,728	6,98	0,49	512	1,140	45 HRA	16,30	45 HRA
		2M3	54,766	7,03	0,43	590	2,005	50 HRA	14,16	50 HRA
		2M4	54,772	7,01	0,41	612	2,005	51 HRA	14,16	51 HRA
0,5% C	CN	5M	54,750	7,04	0,45			44 HRC	7,53	44 HRC
		5M1	54,863	7,04	0,25	505	0,456	45 HRC	5,51	45 HRC
		5M2	54,840	7,02	0,29	507	0,457	44 HRC	4,74	44 HRC
		5M3	54,961	7,00	0,07	416	0,349	45 HRC	1,97	45 HRC
		5M4	54,954	6,97	0,08	340	0,426	45 HRC	1,96	45 HRC
	C	5M	54,664	7,02	0,61			39 HRC	11,45	39 HRC
		5M1	54,815	7,01	0,34	697	0,685	42 HRC	9,00	42 HRC
		5M2	54,791	6,96	0,38	681	0,583	38 HRC	4,03	38 HRC
		5M3	54,907	7,03	0,17	417	0,350	42 HRC	3,14	42 HRC
		5M4	54,893	7,04	0,19	386	0,338	41 HRC	3,44	41 HRC
	S/TT	5M	54,688	7,02	0,57	476	2,258	41 HRA	14,33	41 HRA
		5M1	54,806	7,00	0,35	604	0,940	51 HRA	10,05	51 HRA
		5M2	54,801	6,99	0,36	566	0,976	50 HRA	11,07	50 HRA
		5M3	54,860	6,97	0,25	581	0,693	58 HRA	9,85	58 HRA
		5M4	54,878	6,95	0,22	567	0,616	59 HRA	7,38	59 HRA
0,8% C	CN	8M	54,797	6,99	0,37	677	0,473	51 HRC	2,68	48 HRC
		8M1	54,928	6,99	0,13	371	0,256	50 HRC	2,09	46 HRC
		8M2	54,904	6,98	0,18	478	0,366	50 HRC	2,24	46 HRC
		8M3	55,000	6,95	0,00	353	0,244	51 HRC	2,09	45 HRC
		8M4	54,987	6,97	0,02	346	0,252	50 HRC	1,98	47 HRC
	C	8M	54,779	7,03	0,40	806	0,710	44 HRC	9,35	44 HRC
		8M1	54,872	7,00	0,23	651	0,662	39 HRC	8,23	39 HRC
		8M2	54,863	7,03	0,25	637	0,906	40 HRC	7,21	40 HRC
		8M3	54,927	6,98	0,13	384	0,332	40 HRC	2,48	40 HRC
		8M4	54,925	7,00	0,14	417	0,383	40 HRC	3,98	40 HRC
	S/TT	8M	54,777	7,02	0,41	527	2,122	46 HRA	13,72	46 HRA
		8M1	54,908	6,96	0,17	442	0,376	57 HRA	6,40	57 HRA
		8M2	54,875	6,98	0,23	472	0,424	55 HRA	5,95	55 HRA
		8M3	54,921	6,93	0,14	393	0,328	63 HRA	3,97	63 HRA
		8M4	54,906	6,96	0,17	424	0,331	63 HRA	4,97	63 HRA

			1180 1NC 8m/h							
			Propietats generals			UTS			Charpy	
			Longitud sinter. (mm)	Densitat sinter. (g/cm^3)	Var.Dim. (%) [Shrinkage]	UTS (MPa)	ε (%)	Hv	IE (J/cm^2)	Hv superfície
0,2% C	CN	2M	54,648	7,05	0,64	779	0,624	40 HRC	8,24	40 HRC
		2M1	54,847	7,01	0,28	592	0,474	41 HRC	6,02	41 HRC
		2M2	54,835	7,00	0,30	644	0,537	42 HRC	5,57	42 HRC
		2M3	54,947	7,02	0,10	453	0,432	44 HRC	3,24	44 HRC
		2M4	54,973	7,00	0,05	431	0,392	44 HRC	2,74	44 HRC
	C	2M	54,661	7,05	0,62	898,5	0,756	37 HRC	11,10	37 HRC
		2M1	54,806	6,99	0,35	796,5	0,715	39 HRC	10,51	39 HRC
		2M2	54,795	7,02	0,37	772	0,677	40 HRC	7,83	40 HRC
		2M3	54,940	7,01	0,11	525,5	0,430	43 HRC	3,50	43 HRC
		2M4	54,979	7,00	0,04	526	0,427	42 HRC	3,27	42 HRC
	S/TT	2M	54,621	6,99	0,69	336	7,210	29 HRA	25,90	29 HRA
		2M1	54,725	7,05	0,50	560	3,188	47 HRA	28,57	47 HRA
		2M2	54,722	7,02	0,51	511	3,133	47 HRA	29,65	47 HRA
		2M3	54,761	7,06	0,43	624	2,399	51 HRA	26,31	51 HRA
		2M4	54,772	7,04	0,41	592	2,719	49 HRA	27,99	49 HRA
0,5% C	CN 6m	5M	54,678	7,04	0,59	748	0,514	40 HRC	8,45	40 HRC
		5M1	54,843	7,04	0,29	570	0,548	44 HRC	6,07	44 HRC
		5M2	54,821	7,01	0,33	561	0,492	43 HRC	4,78	43 HRC
		5M3	54,932	6,99	0,12	466	0,369	44 HRC	1,98	44 HRC
		5M4	54,896	6,97	0,19	439	0,352	43 HRC	1,97	43 HRC
	C	6m	54,707	7,01	0,53	903	0,717	41 HRC	9,41	41 HRC
		5M1	54,826	7,00	0,32	751	0,662	41 HRC	8,03	41 HRC
		5M2	54,795	7,00	0,37	721	0,652	41 HRC	8,06	41 HRC
		5M3	54,922	7,04	0,14	498	0,396	43 HRC	2,95	43 HRC
		5M4	54,900	7,04	0,18	440	0,386	41 HRC	2,94	41 HRC
	S/TT	5M	54,661	7,06	0,62	498	2,875	45 HRA	19,47	45 HRA
		5M1	54,799	7,06	0,37	604	1,203	51 HRA	18,28	51 HRA
		5M2	54,770	7,09	0,42	598	1,498	50 HRA	16,43	50 HRA
		5M3	54,831	7,07	0,31	695	1,193	57 HRA	16,09	58 HRA
		5M4	54,832	7,06	0,31	792	1,738	57 HRA	16,10	57 HRA
0,8% C	CN	8M	54,830	7,03	0,31	542	0,423	48 HRC	2,80	48 HRC
		8M1	54,968	6,99	0,06	529	0,472	40 HRC	2,72	40 HRC
		8M2	54,955	7,00	0,08	595	0,501	40 HRC	3,96	40 HRC
		8M3	55,022	6,93	-0,04	404	0,371	41 HRC	1,97	41 HRC
		8M4	54,989	6,98	0,02	425	0,330	43 HRC	1,99	43 HRC
	C	8M	54,742	7,02	0,47	804	0,568	45 HRC	5,34	45 HRC
		8M1	54,893	7,04	0,20	726	0,758	45 HRC	3,46	45 HRC
		8M2	54,874	7,01	0,23	680	0,574	46 HRC	3,97	46 HRC
		8M3	54,941	7,01	0,11	463	0,388	47 HRC	1,98	47 HRC
		8M4	54,898	6,99	0,19	543	0,456	47 HRC	1,98	47 HRC
	S/TT	8M	54,777	7,02	0,41	528	2,215	45 HRA	17,79	45 HRA
		8M1	54,908	6,96	0,17	631	0,874	56 HRA	9,84	56 HRA
		8M2	54,875	6,98	0,23	618	0,884	57 HRA	9,92	57 HRA
		8M3	54,921	6,93	0,14			63 HRA	7,44	63 HRA
		8M4	54,906	6,96	0,17			65 HRA	7,46	65 HRA

APPENDIX 2: PROPERTIES CATALOGUE: ASTALOY FE-85MO

Astaloy 85 Mo



Typical data, Astaloy 85 Mo

Apparent density, g/cm^3	Flow, sec/50g
3.1	25

With inhibitor admixed

Sieve analys, %

+212 μm	0
+150 μm	15
-45 μm	20

Compressibility, g/cm^3

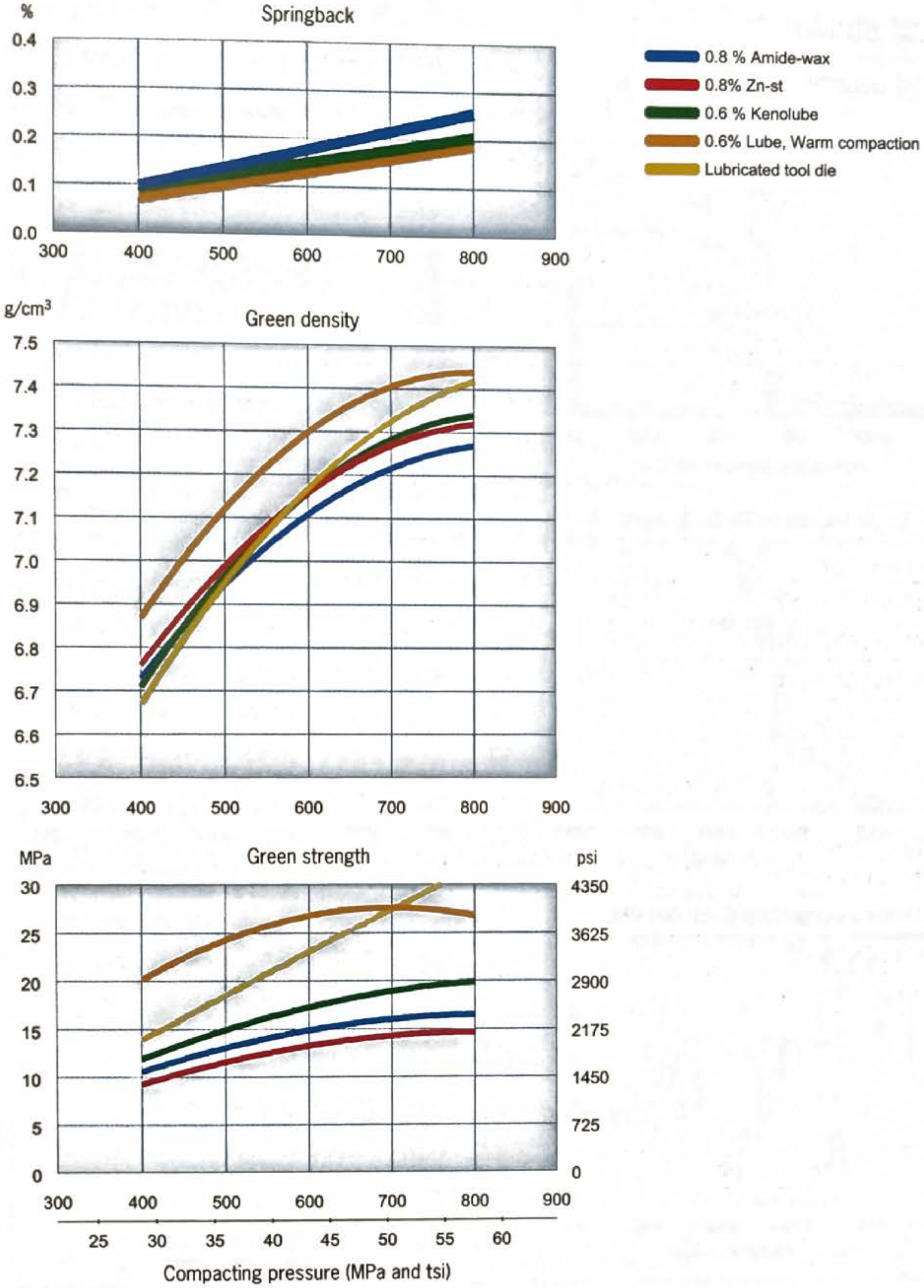
Compacting pressure	Lubricated die	0.8% Zn-st	0.6% Kenolube P11
400 MPa (28.8 tsi)	6.67	6.76	6.71
600 MPa (43.2 tsi)	7.17	7.16	7.16
800 MPa (57.6 tsi)	7.42	7.32	7.34

Green strength, MPa (10^3 psi)

Compacting pressure	Lubricated die	0.8% Zn-st	0.6% Kenolube P11
400 MPa (28.8 tsi)	14 (2.0)	9 (1.3)	12 (1.7)
600 MPa (43.2 tsi	23 (3.3)	13 (1.9)	17 (2.5)
800 MPa (57.6 tsi)	32 (4.6)	15 (2.1)	20 (2.9)

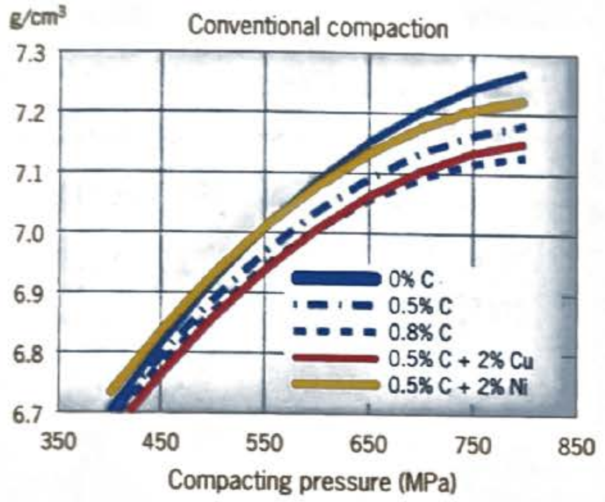
Chemical analysis, %

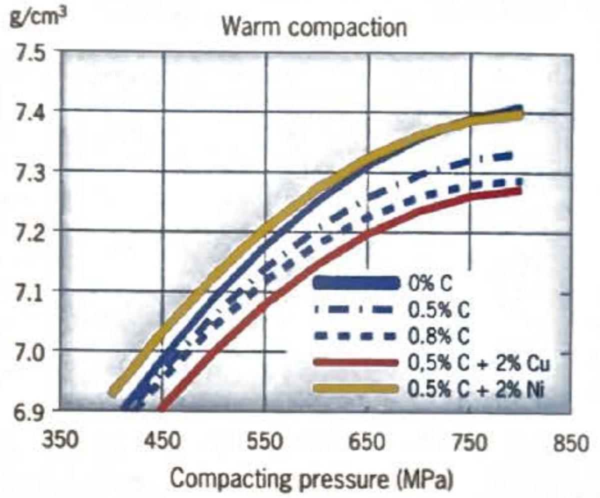
Carbon	<0.01
O-tot	0.1
Molybdenum	0.85

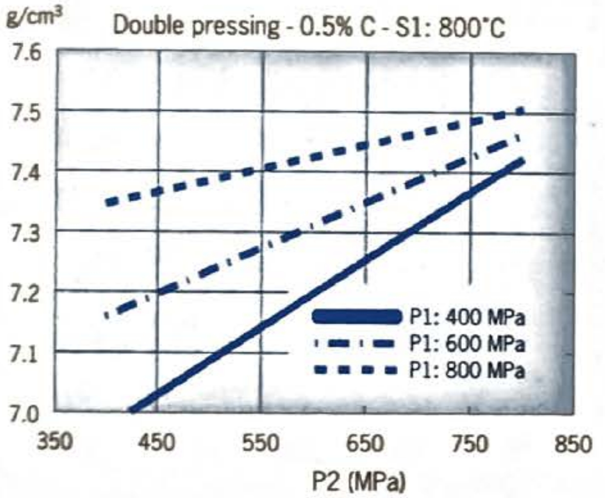

Springback
%
0.4
0.3
0.2
0.1
0.0
300
400
500
600
700
800
900
0.8 % Amide-wax
0.8% Zn-st
0.6 % Kenolube
0.6% Lube, Warm compaction
Lubricated tool die
Green density
g/cm³
7.5
7.4
7.3
7.2
7.1
7.0
6.9
6.8
6.7
6.6
6.5
300
400
500
600
700
800
900
Green strength
MPa
psi
30
25
20
15
10
5
0
4350
3625
2900
2175
1450
725
0
300
400
500
600
700
800
900
25
30
35
40
45
50
55
60
Compacting pressure (MPa and tsi)

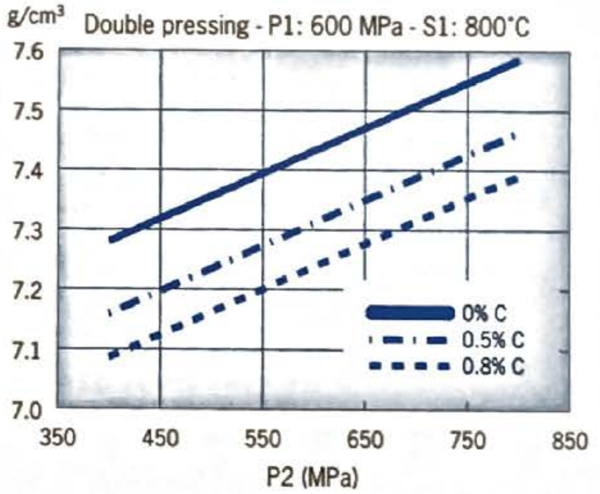
Astaloy 85 Mo

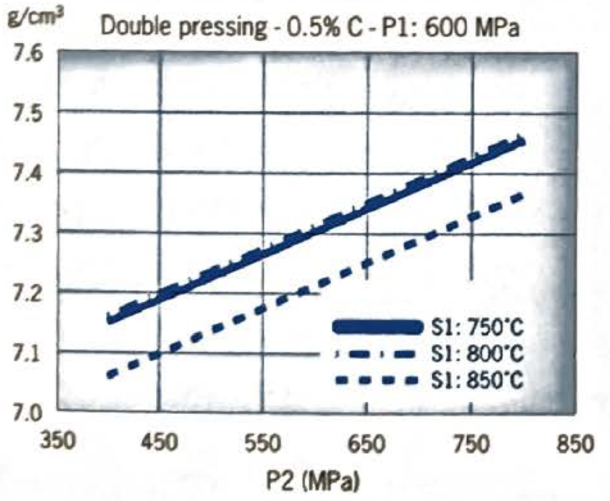
Sintered density







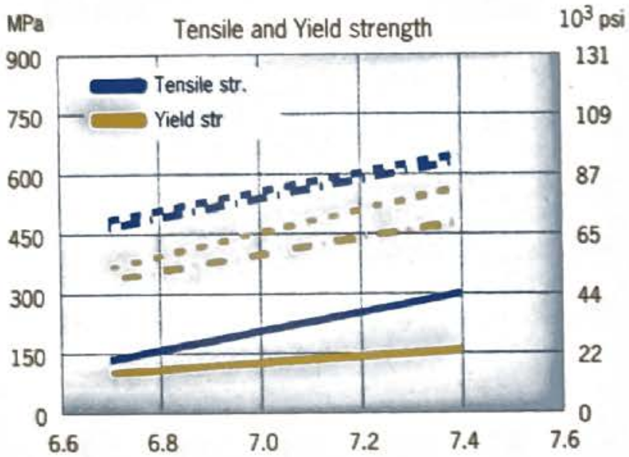


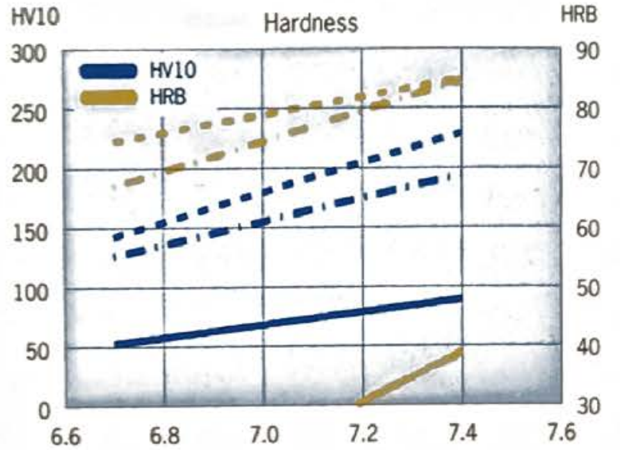


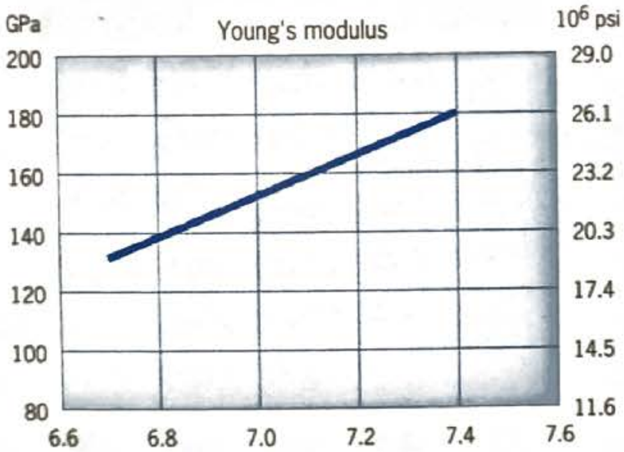
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.

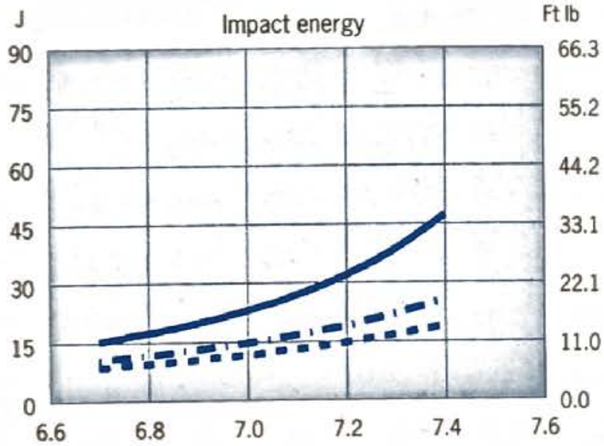
Astaloy 85 Mo + C

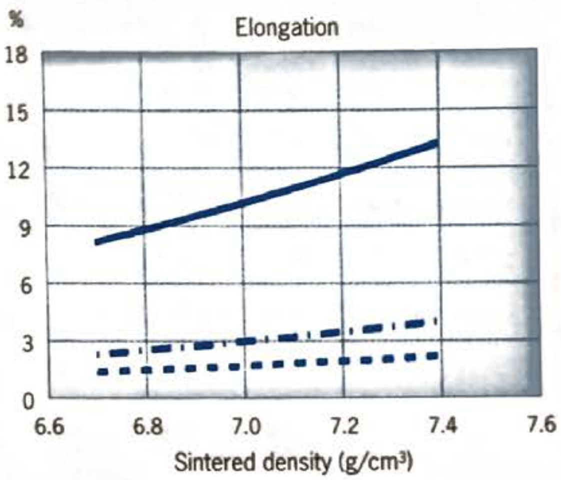
0% C
0.5% C
0.8% C

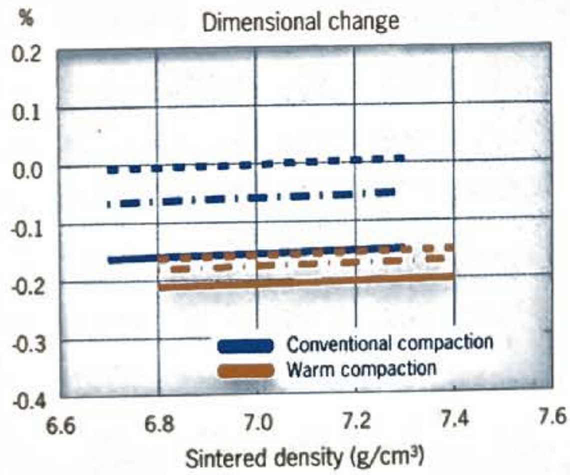






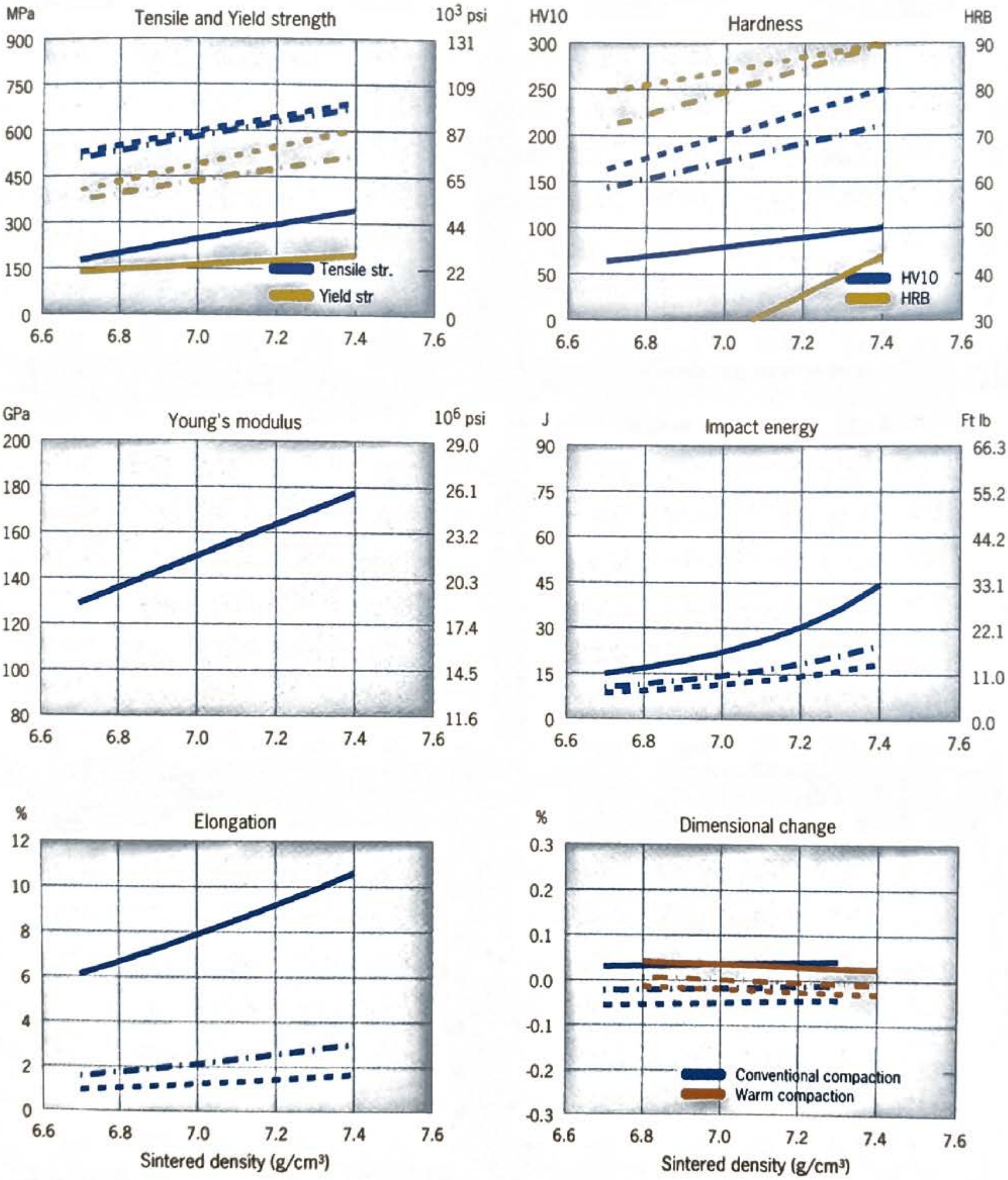






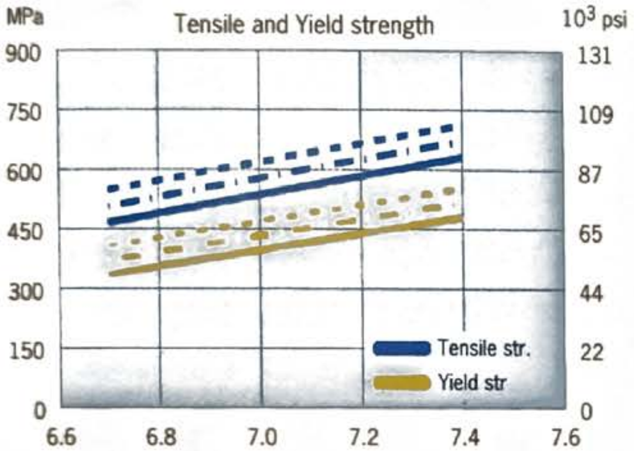
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

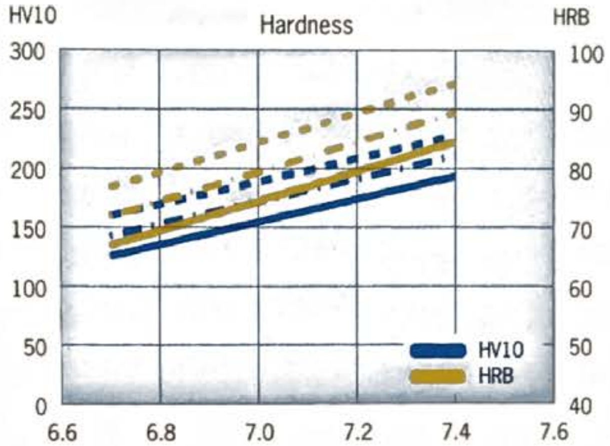
Astaloy 85 Mo + 1% Cu + C

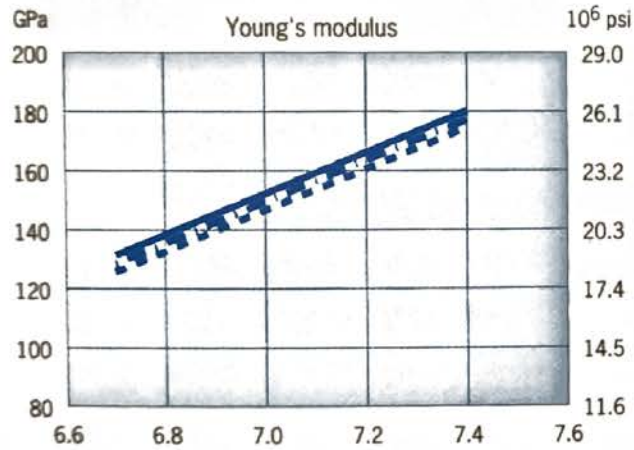


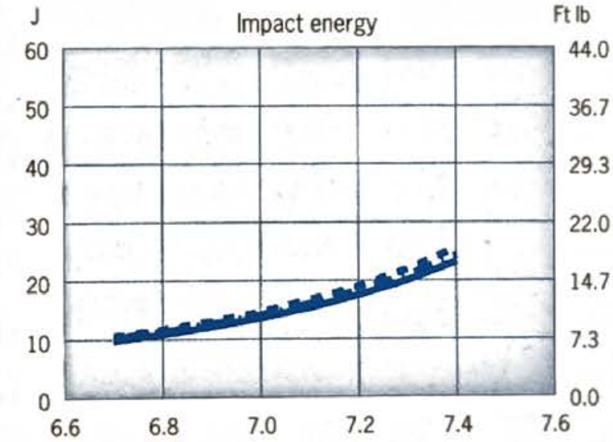
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

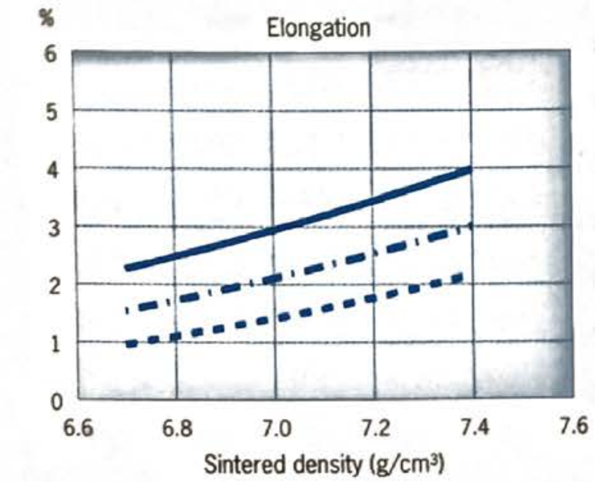
Astaloy 85 Mo + 0.5% C + Cu

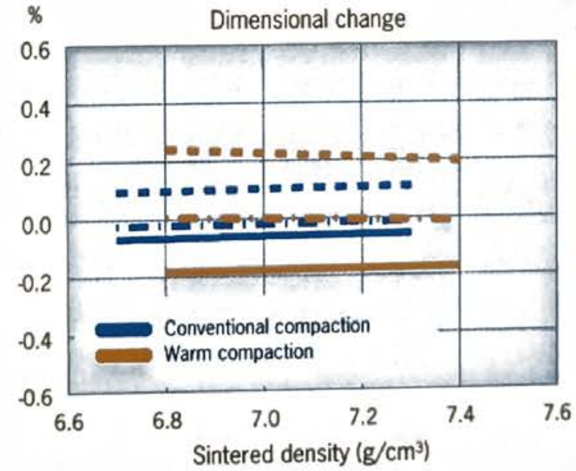






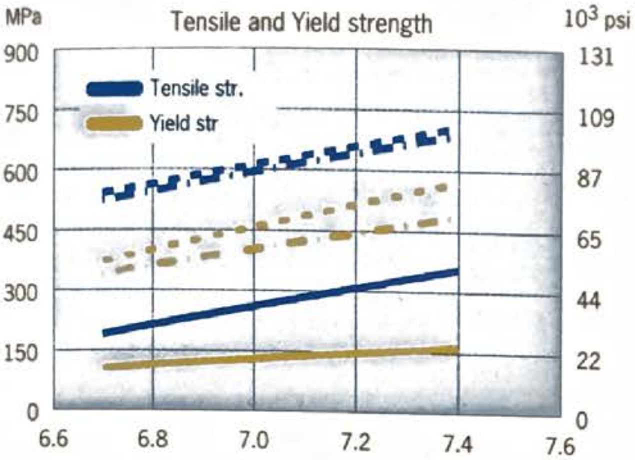


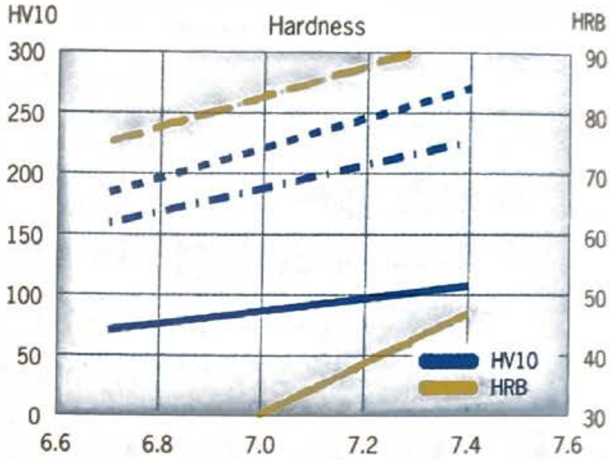


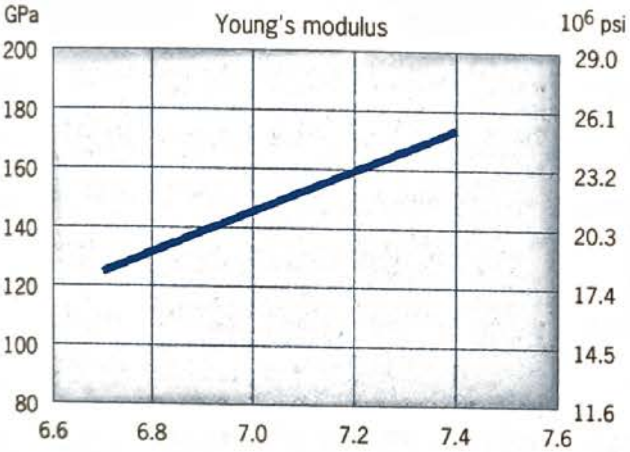


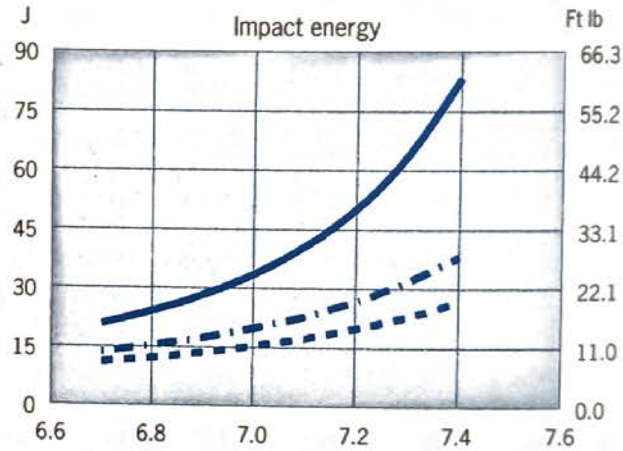
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

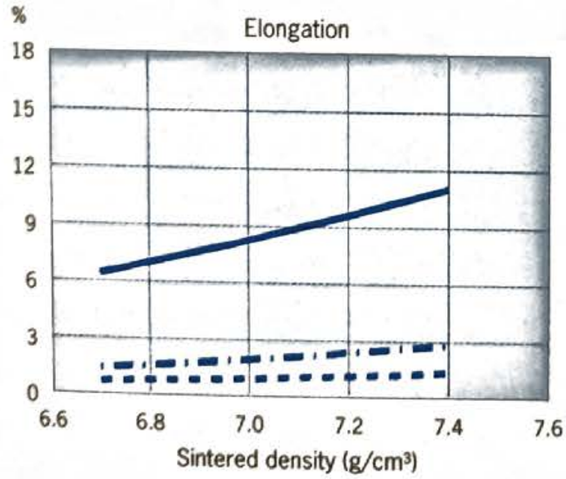
Astaloy 85 Mo + 2% Ni + C

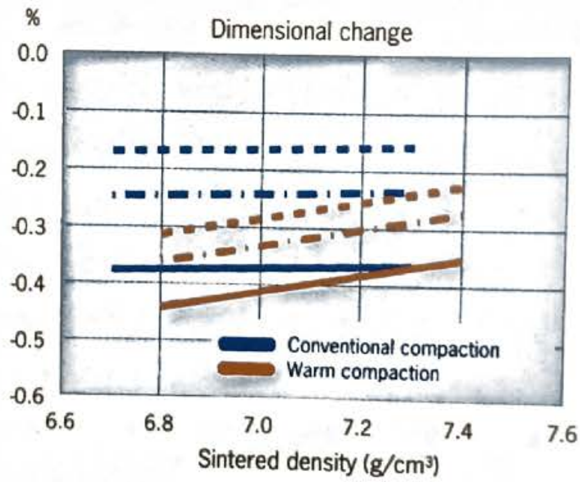








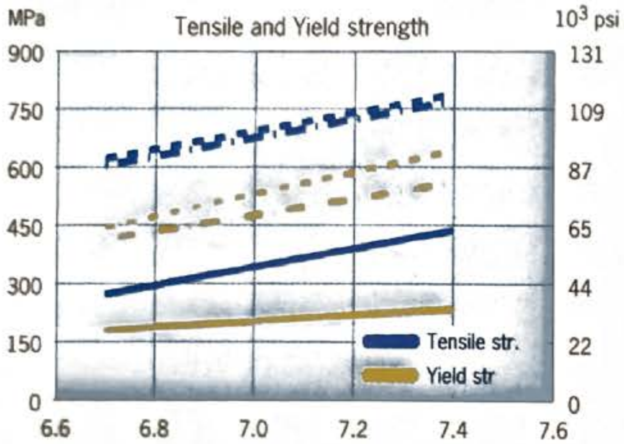


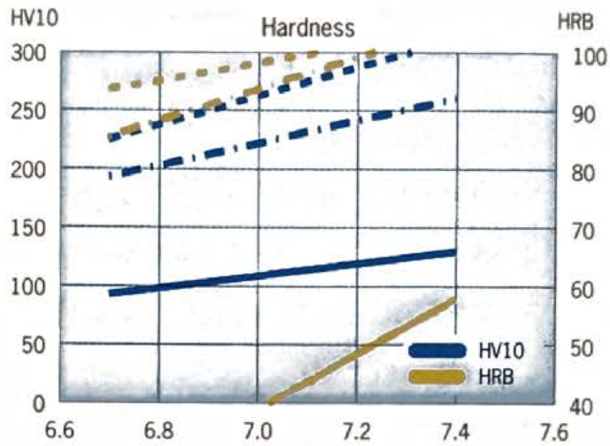


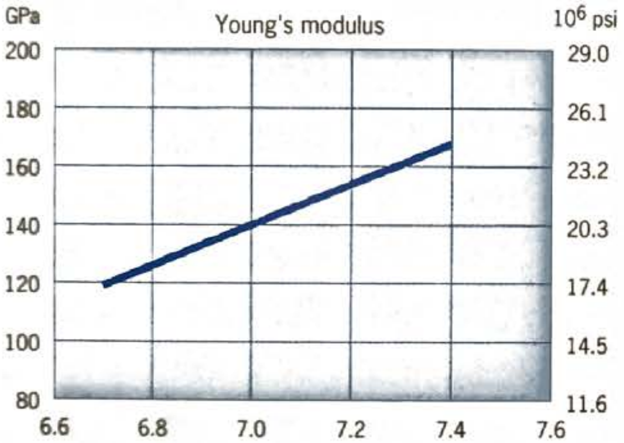
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

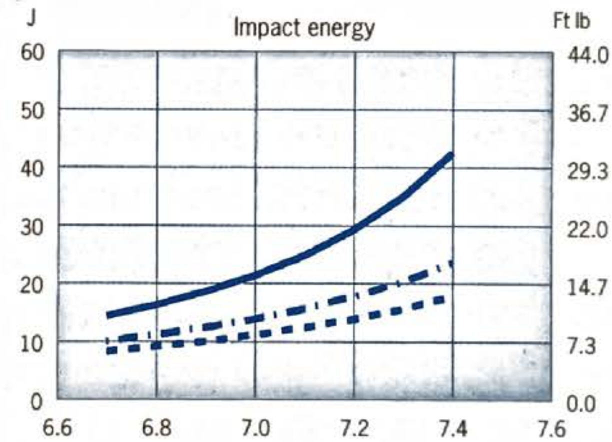
Astaloy 85 Mo + 2% Cu + 2% Ni + C

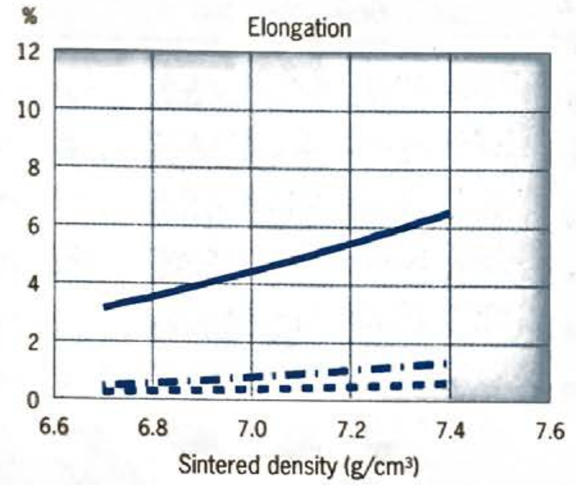
0% C
0.5% C
0.8% C

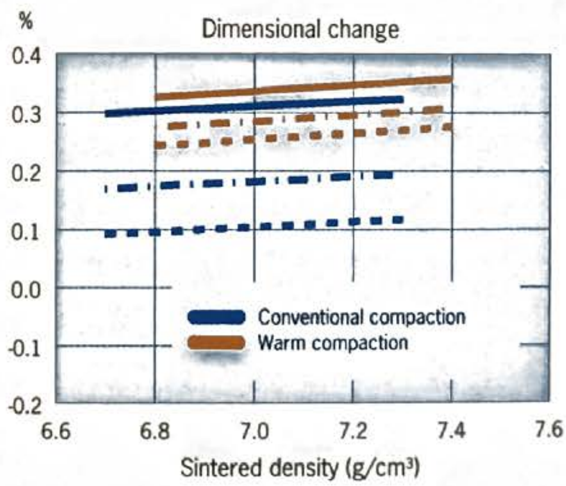








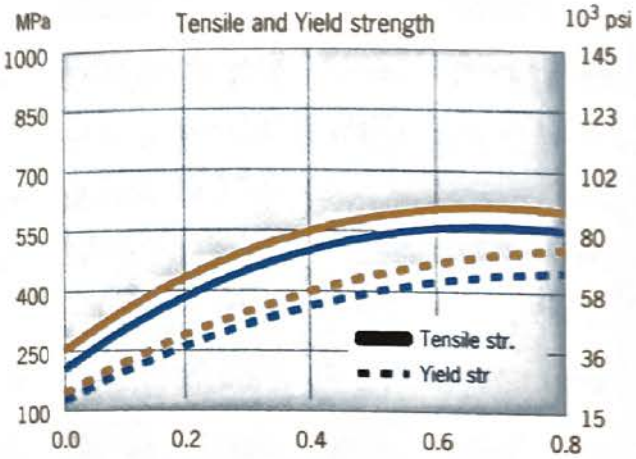


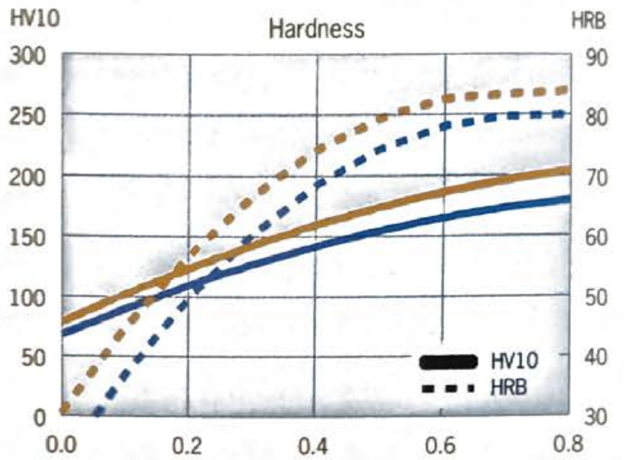


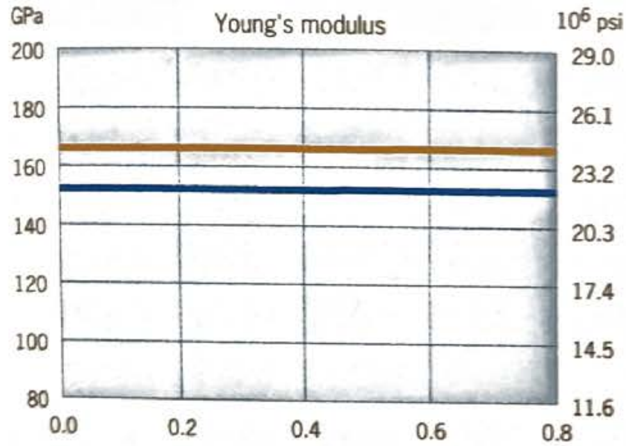
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

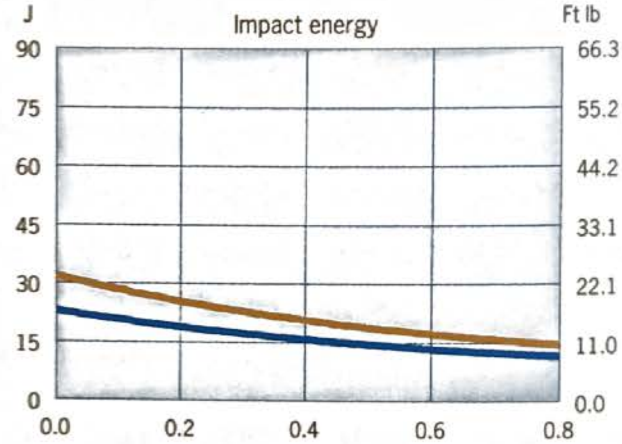
Astaloy 85 Mo + C

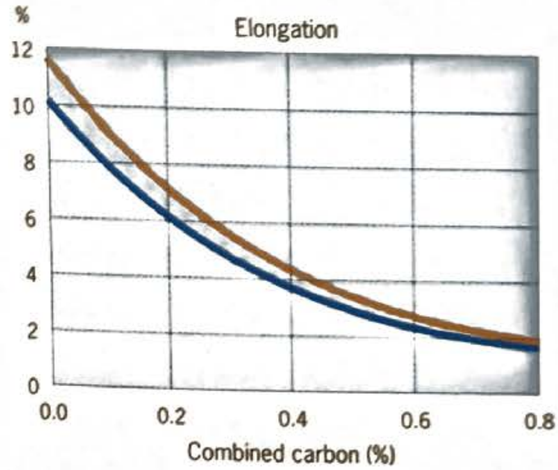
Conventional compaction SD=7.0 g/cm³
Warm compaction SD=7.2 g/cm³

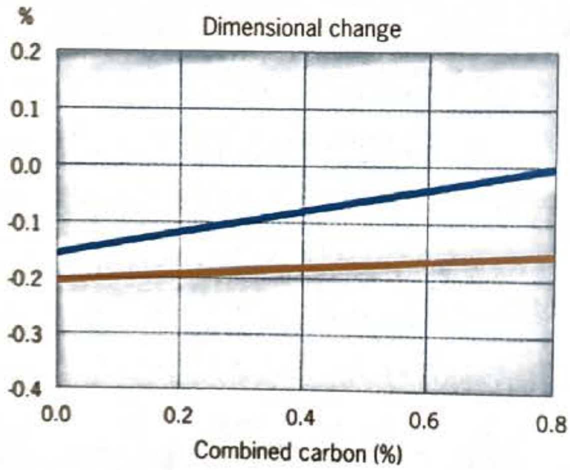








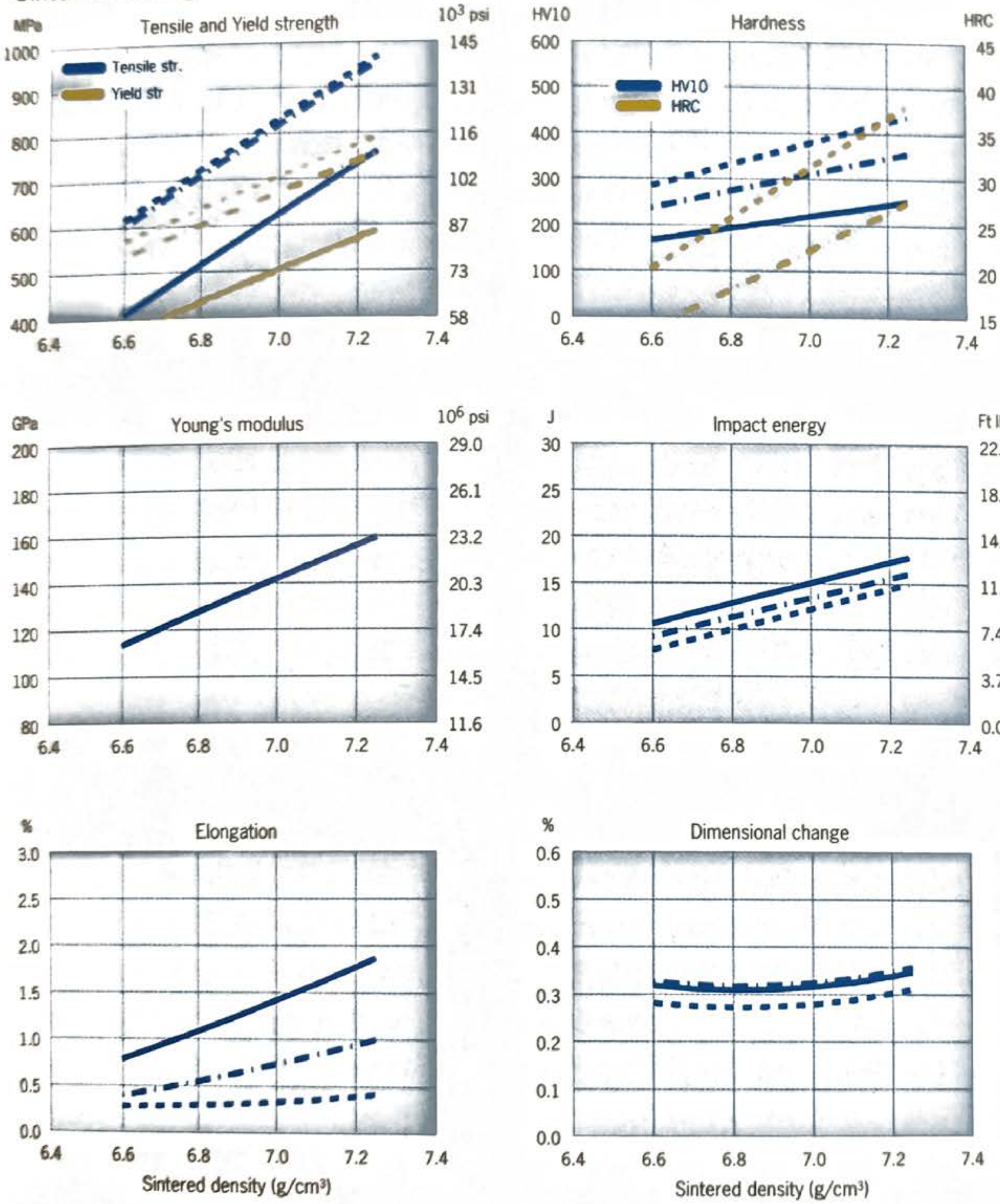




MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube respectively; P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 90/10 N_2/H_2.
Dimensional change: Green to as sintered.

Astaloy 85 Mo + 2% Cu + C (cooling rate 2.5°C/s)

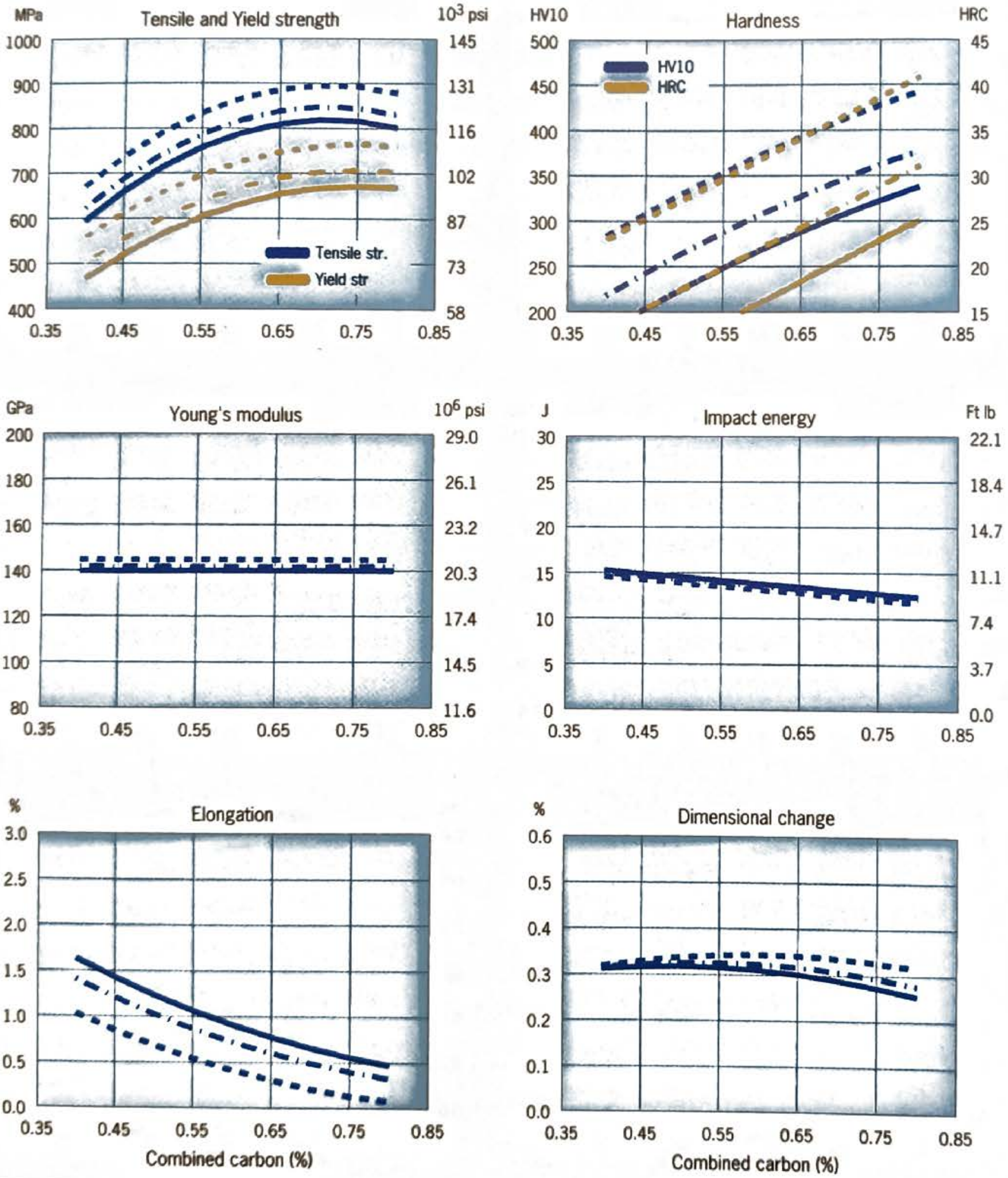
Sinter hardening



MANUFACTURING CONDITIONS: 2% Cu-30 + 0.8% Amide wax and 0.6% Lube resp. P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 80/20 N_2/H_2, convective cooling rate 2.5°C/s. Tempering 180°C (356°F), 60 min in air. Dimensional change: Green to as sintered.

Astaloy 85 Mo + 2% Cu + C (sintered density 7.0 g/cm³)

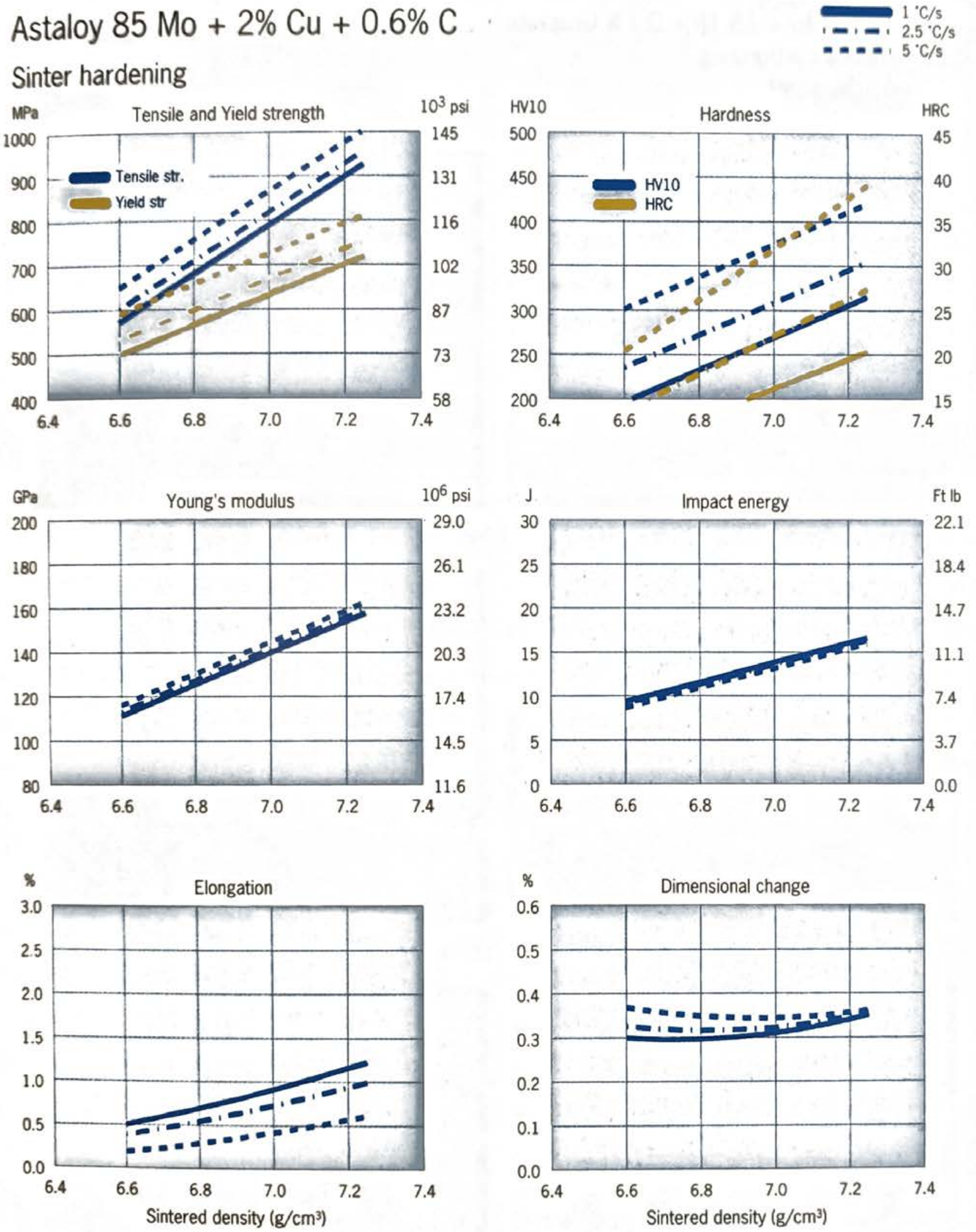
Sinter hardening



MANUFACTURING CONDITIONS: 2% Cu-30 + 0.8% Amide wax and 0.6% Lube resp. P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 80/20 N_2/H_2, various convective cooling rates. Tempering 180°C (356°F), 60 min in air. Dimensional change: Green to as sintered.

Astaloy 85 Mo + 2% Cu + 0.6% C

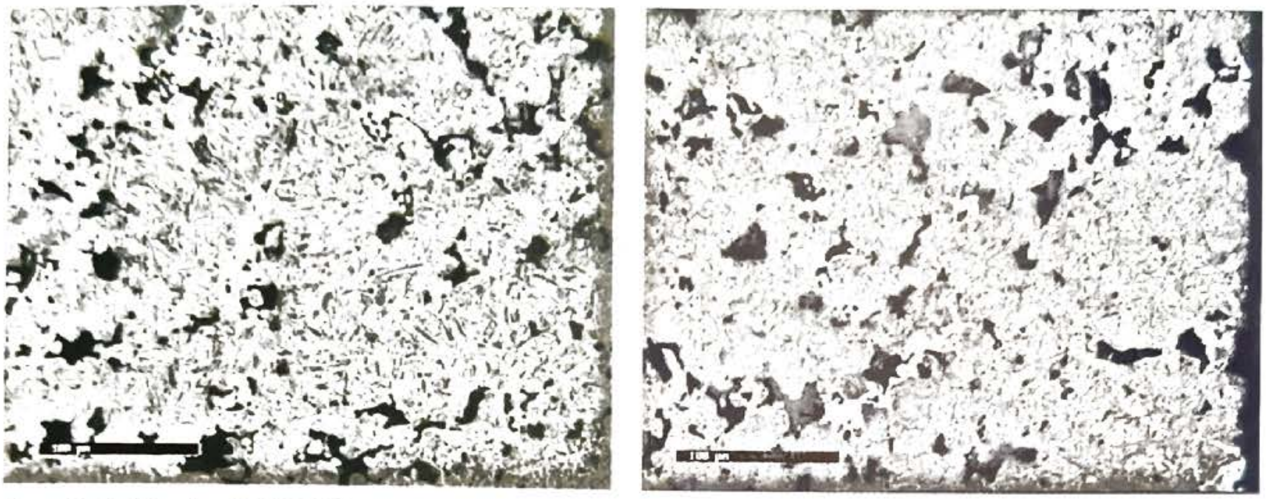
Sinter hardening



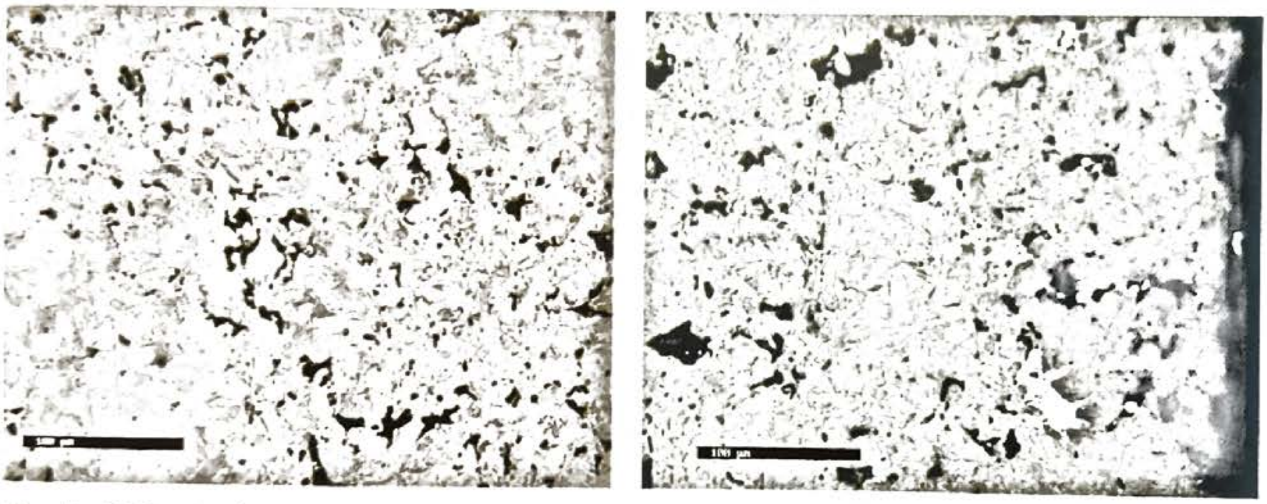
MANUFACTURING CONDITIONS: 2% Cu-30 + 0.8% Amide wax and 0.6% Lube resp. P: 400 - 800 MPa conventional and warm compaction, S: 1120°C (2050°F), 30 min in 80/20 N_2/H_2, various convective cooling rates. Tempering 180°C (356°F), 60 min in air. Dimensional change: Green to as sintered.

Astaloy 85 Mo + 1% Ni + 0.1% Graphite
20 minutes carburizing
Various densities

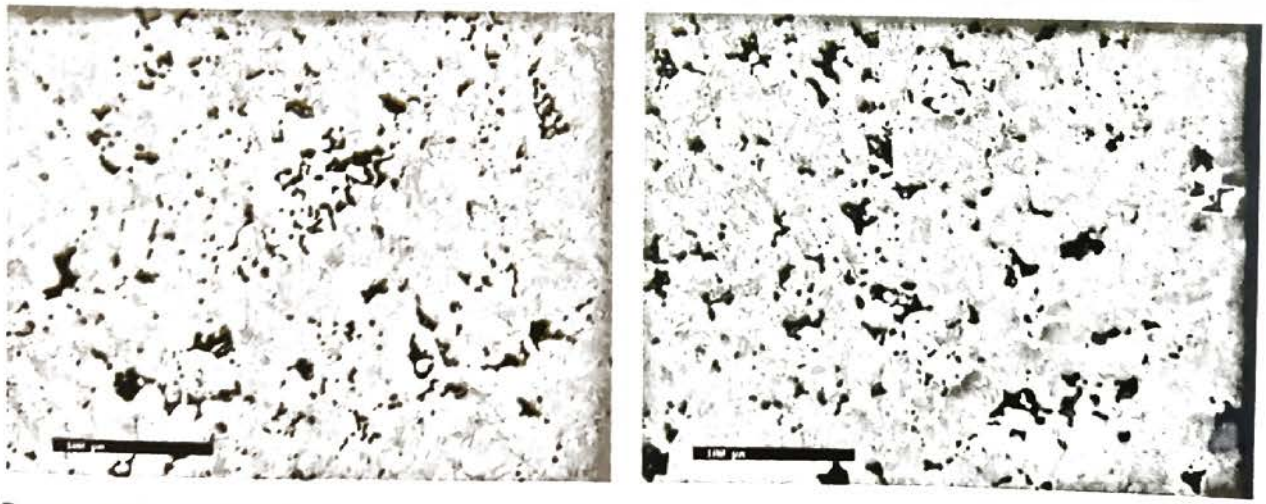
Centre | Surface



Density 7.00 g/cm³ (500 MPa conventional compaction)



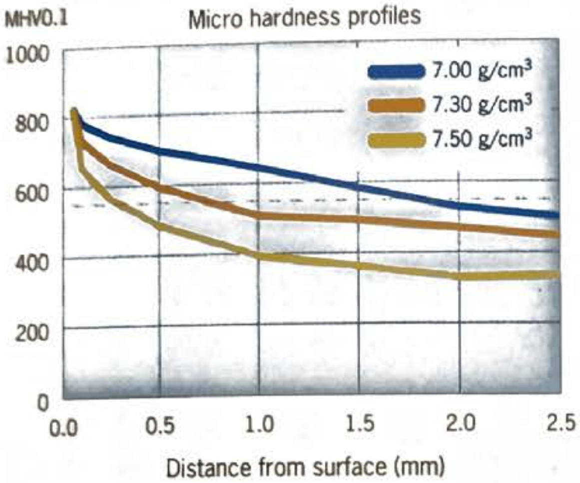
Density 7.30 g/cm³ (800 MPa conventional compaction)

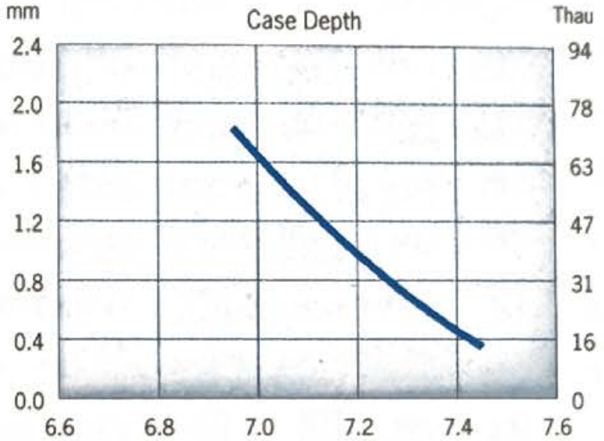


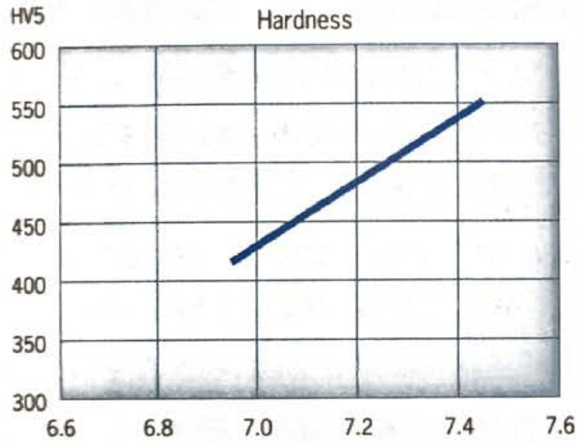
Density 7.50 g/cm³ (800 MPa warm compaction)

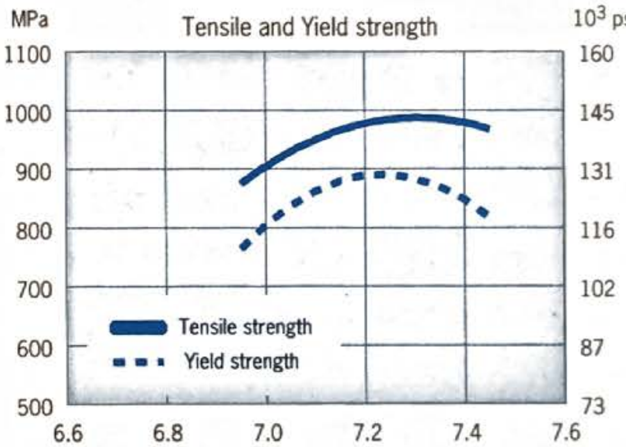
Astaloy 85 Mo + 1% Ni

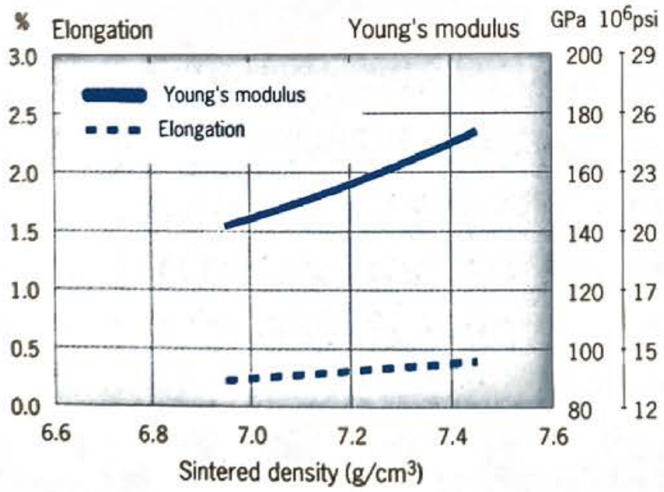
Case hardening

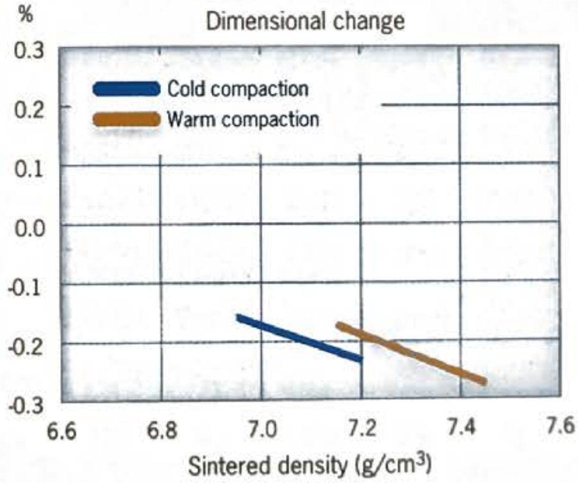








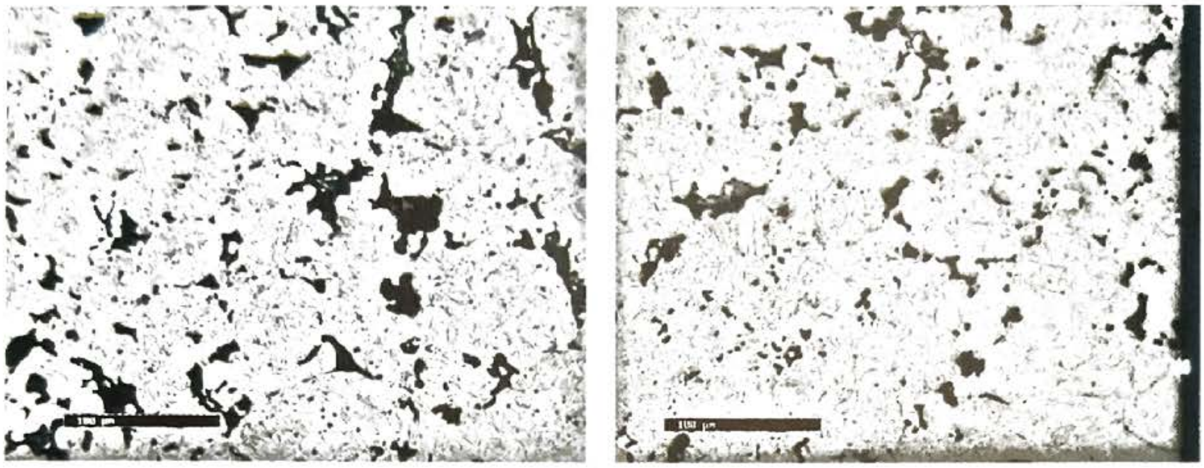




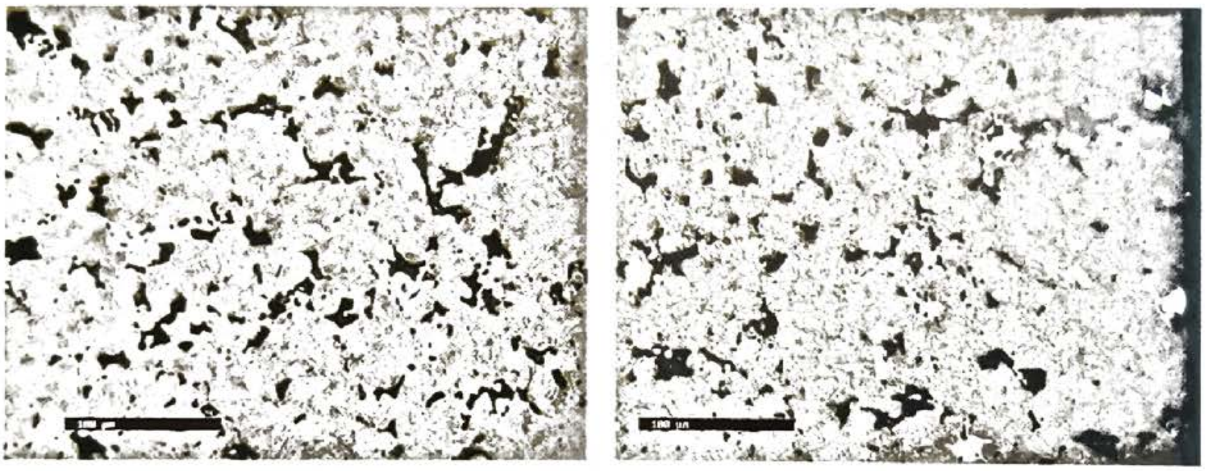
MANUFACTURING CONDITIONS: 0.8% Amide wax and 0.6% Lube resp.; P: 500 MPa and 800 MPa conventional compaction and 800 MPa warm compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), 20 min at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo +1% Ni + 0.1% Graphite
650 MPa conventional compaction (7.20 g/cm3)
Various carburizing time

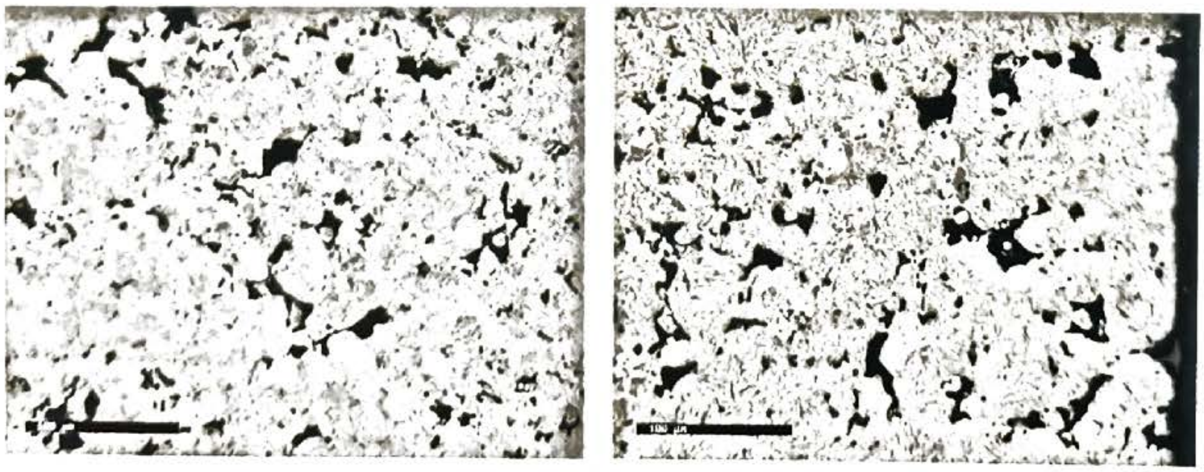
Centre Surface



7 minutes carburizing



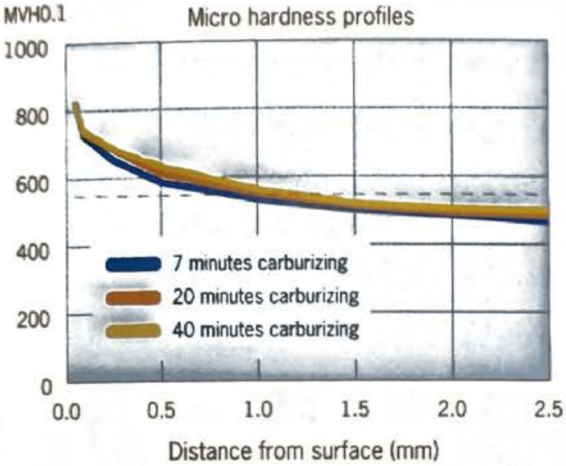
20 minutes carburizing

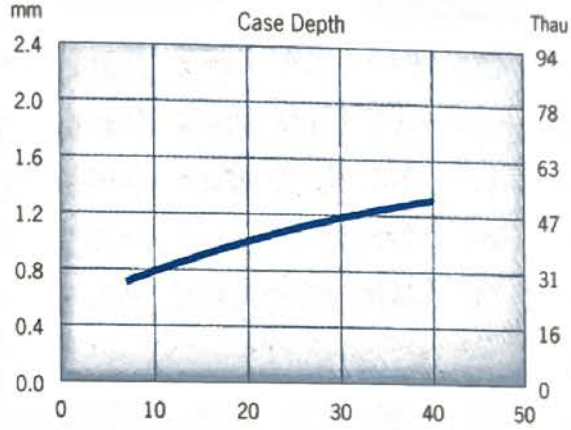


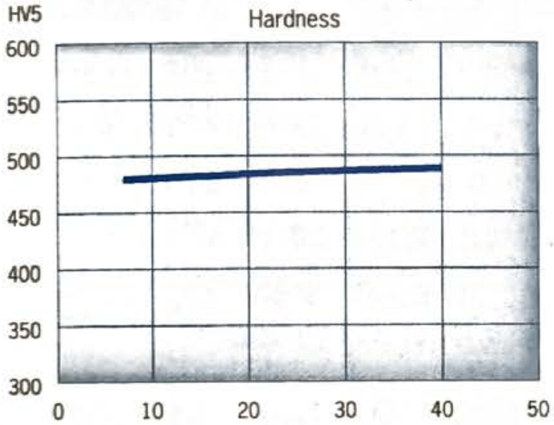
40 minutes carburizing

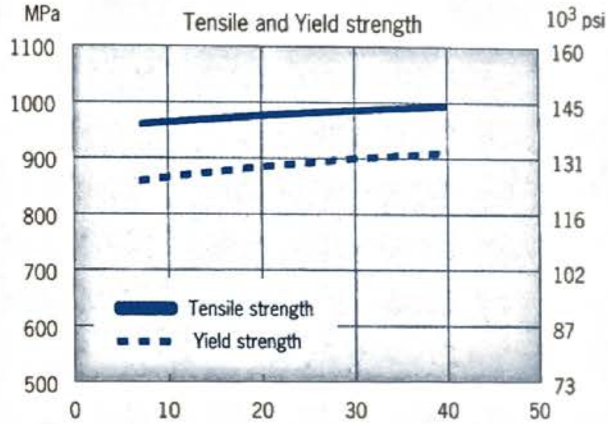
Astaloy 85 Mo + 1% Ni

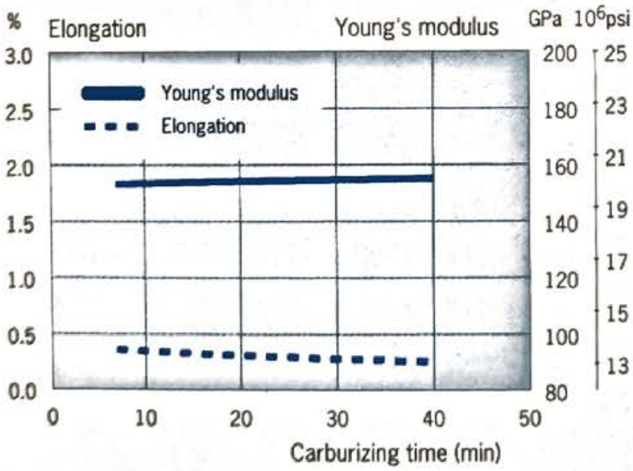
Case hardning

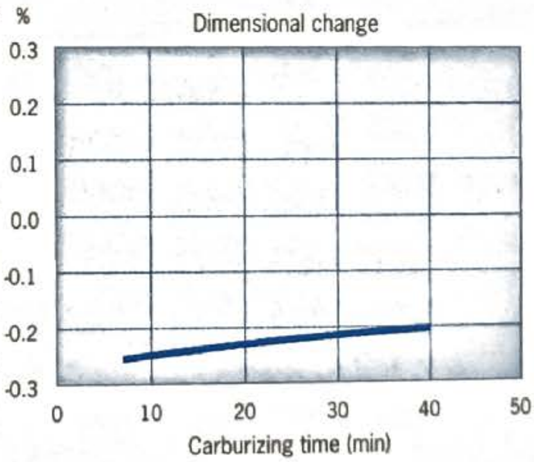








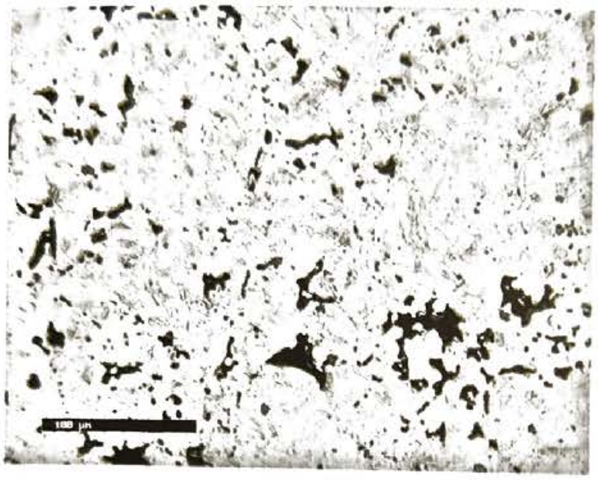
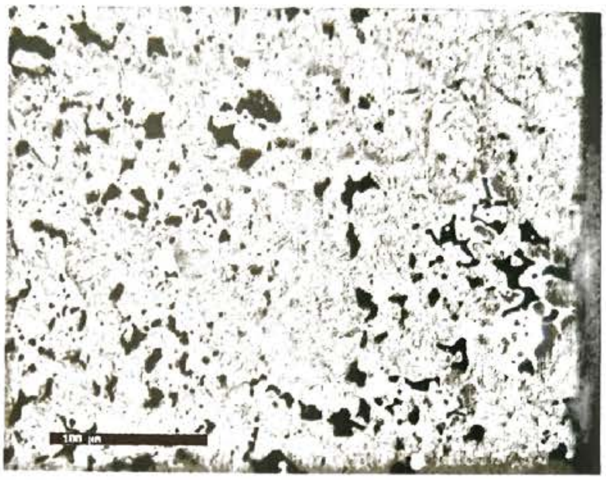




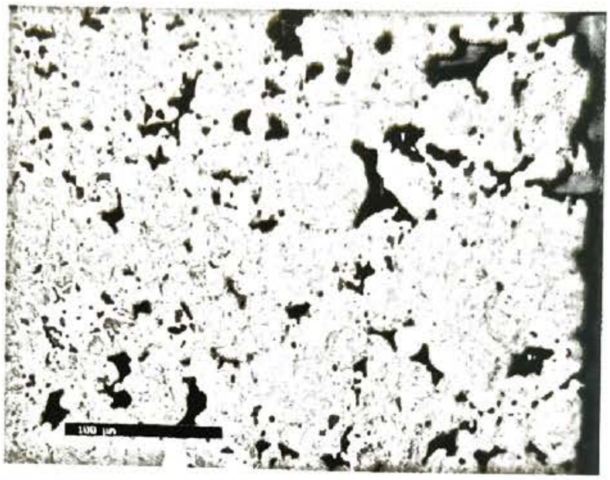
MANUFACTURING CONDITIONS: 0.6% Lube; P: 650 MPa conventional compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), various time at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo +1% Ni + 0.1% Graphite
650 MPa warm compaction (7.40 g/cm3)
Various carburizing time

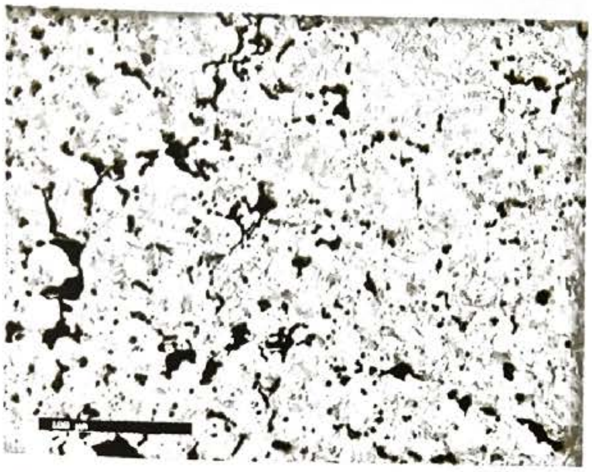
Centre | Surface

7 minutes carburizing

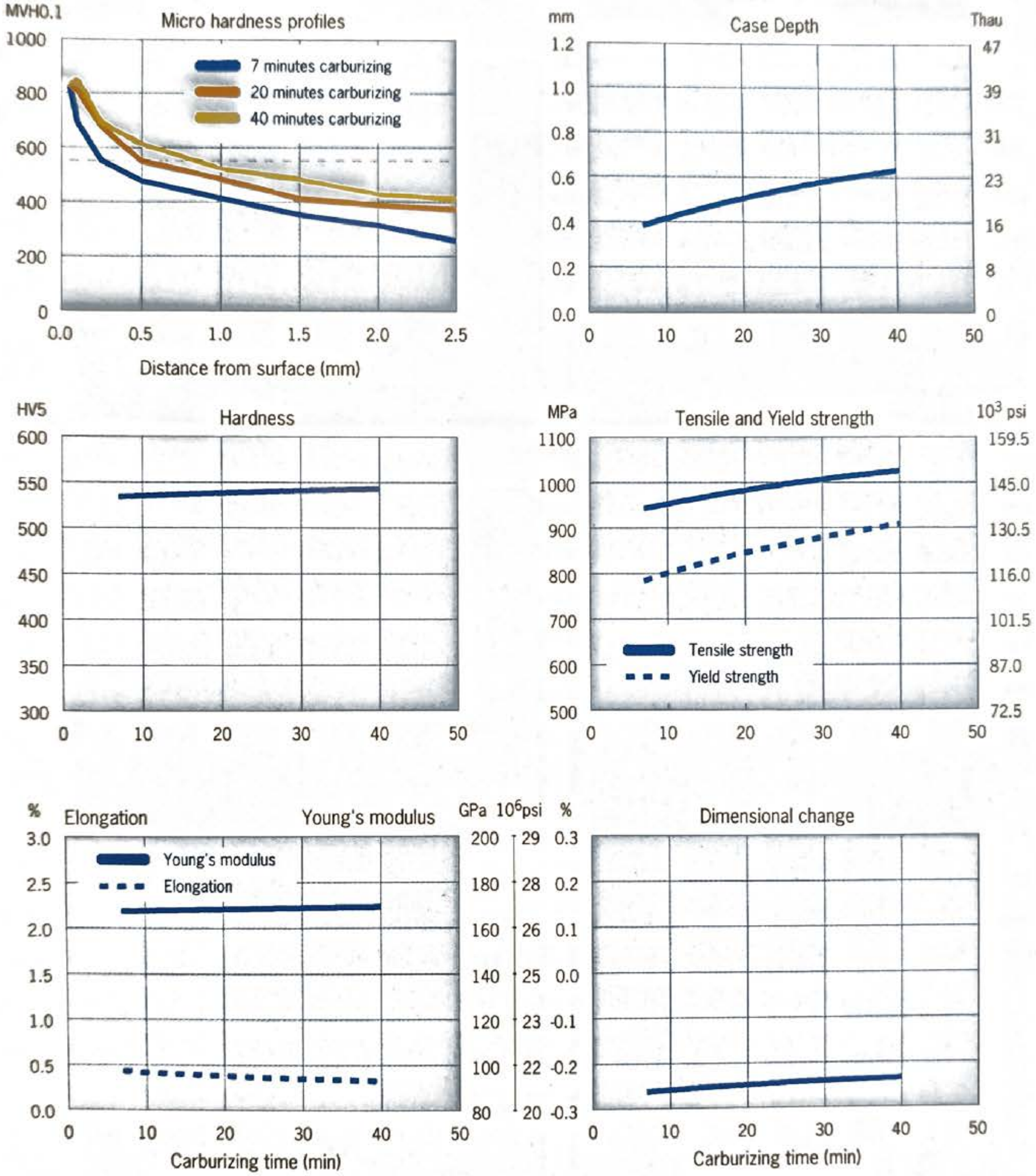
20 minutes carburizing




40 minutes carburizing

Astaloy 85 Mo + 1% Ni

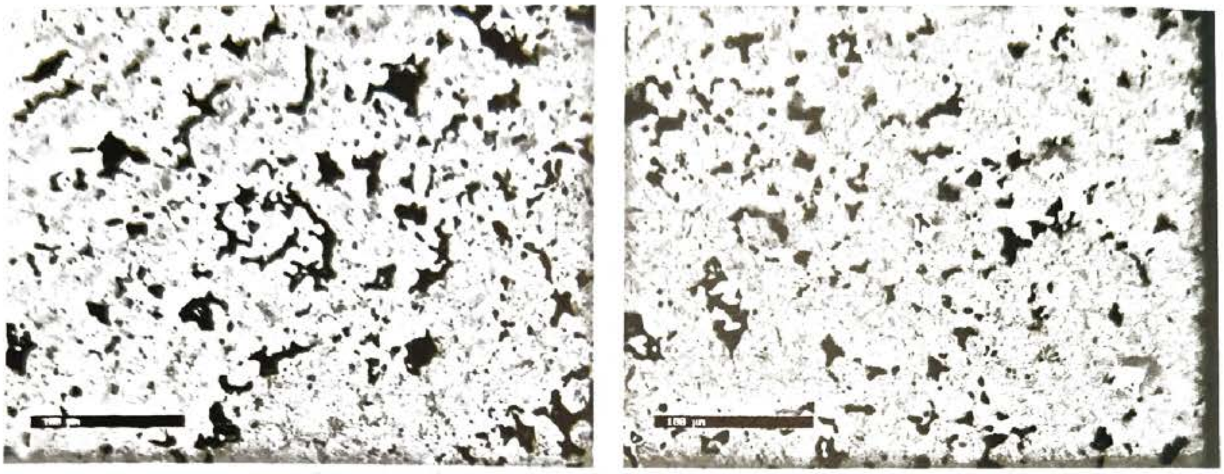
Case hardening



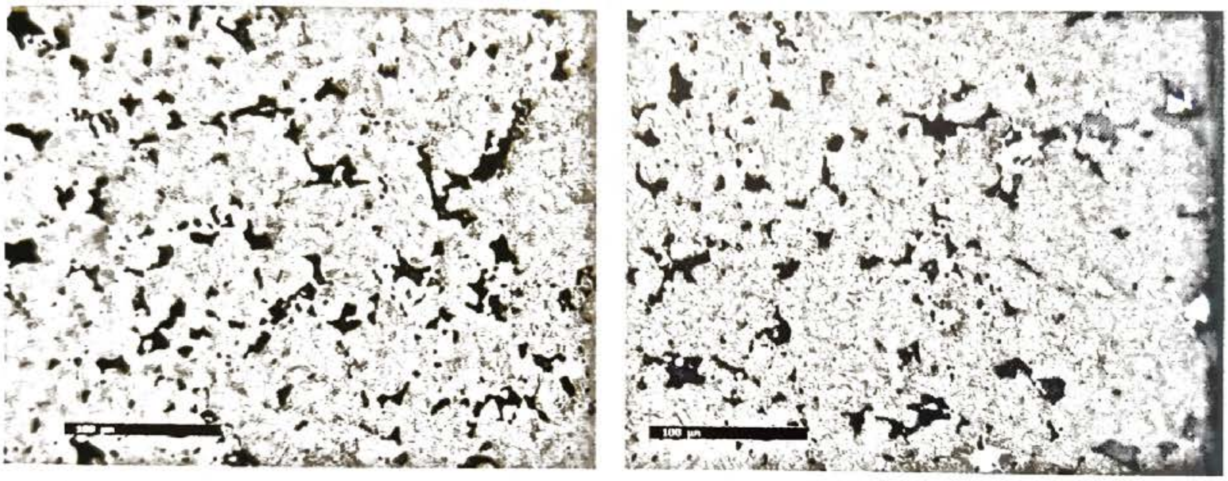
MANUFACTURING CONDITIONS: 0.6% Lube; P: 650 MPa warm compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), various time at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo + 1% Ni
650 MPa conventional compaction (7.20 g/cm³), 20 minutes carburizing
Various graphite additions

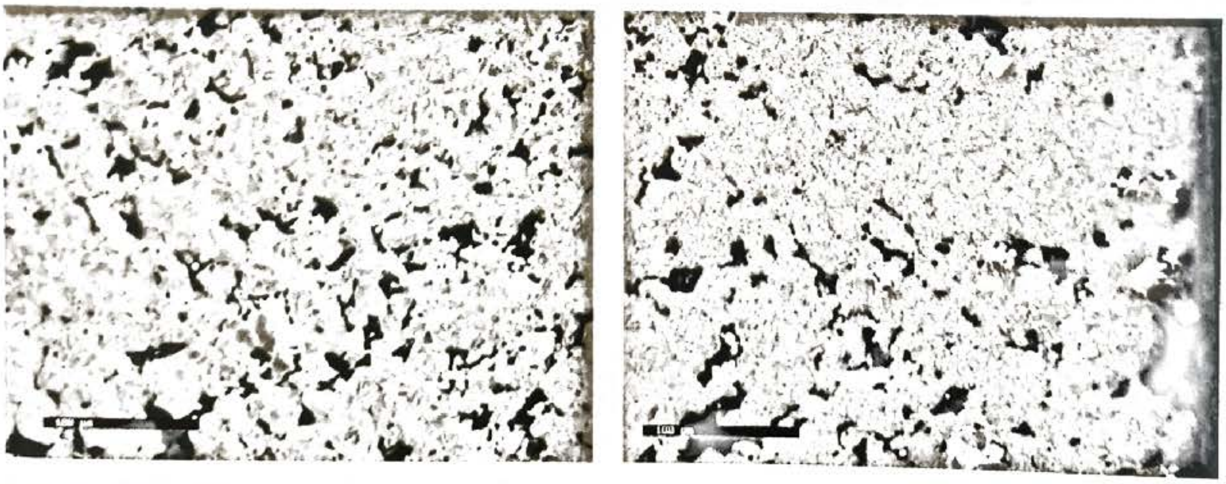
Centre | Surface



No graphite addition



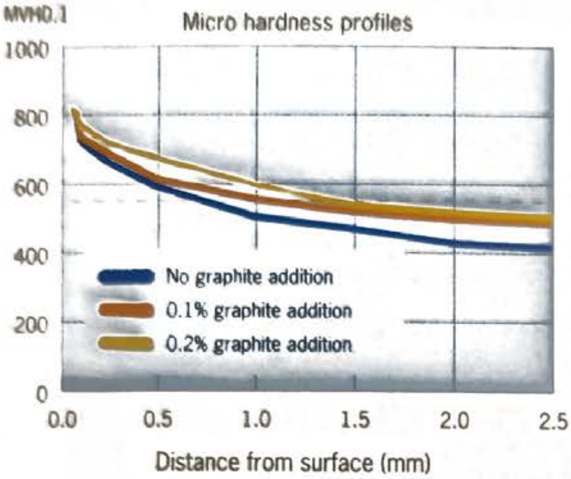
0.1% graphite addition

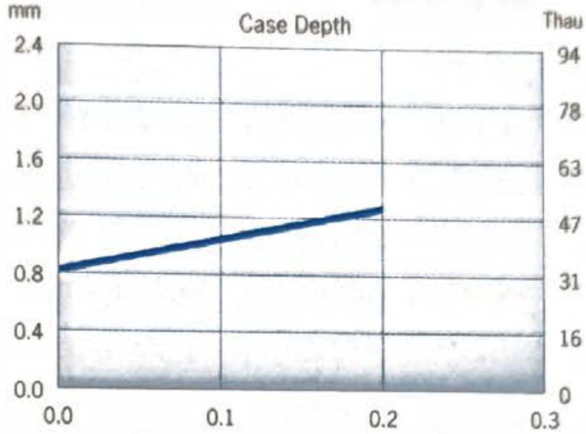


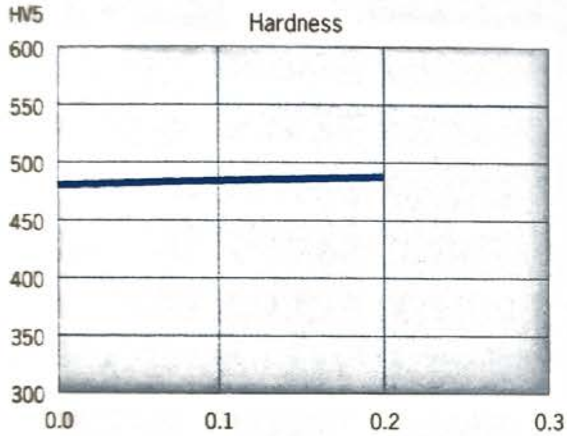
0.2% graphite addition

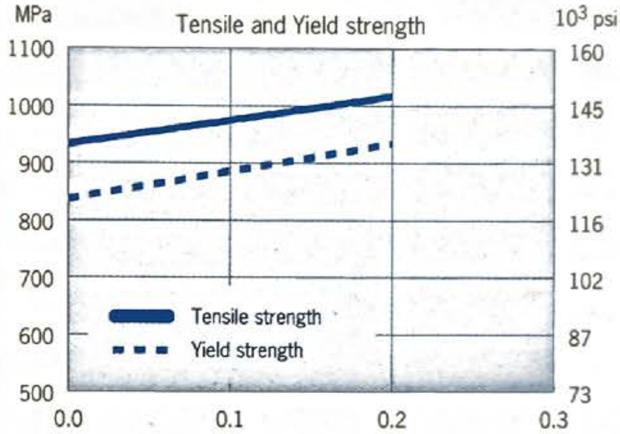
Astaloy 85 Mo + 1% Ni

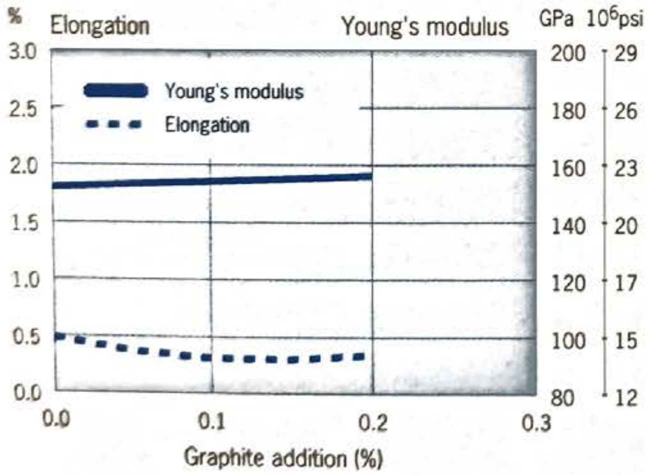
Case hardening

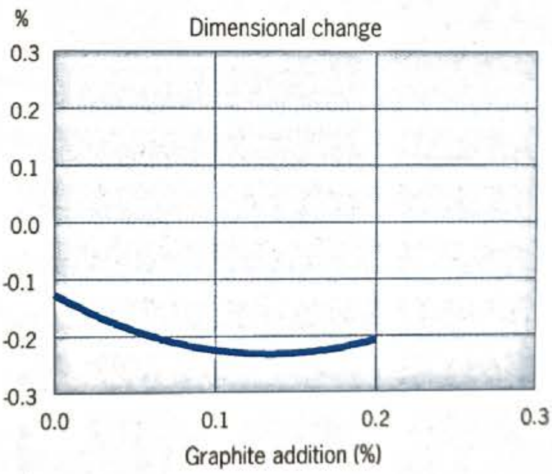








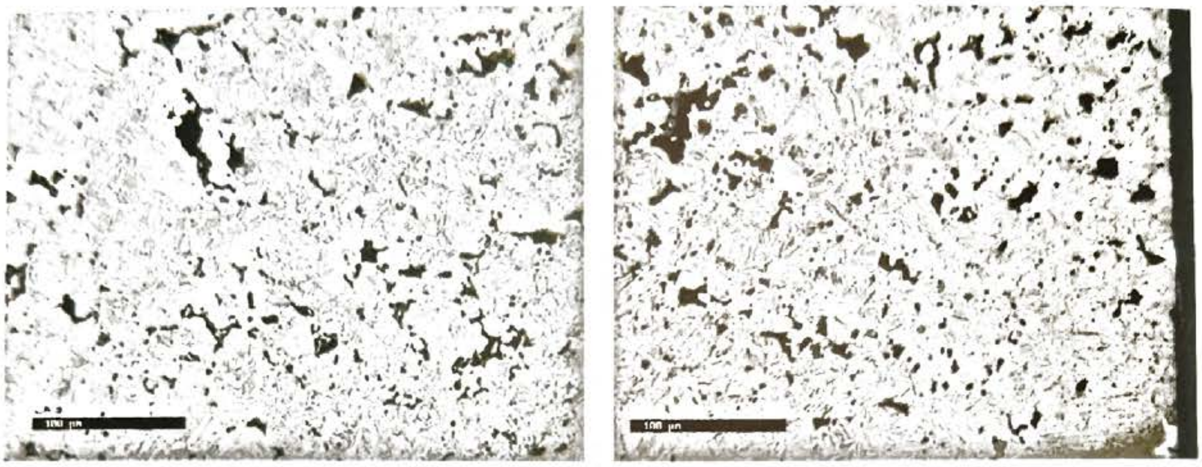




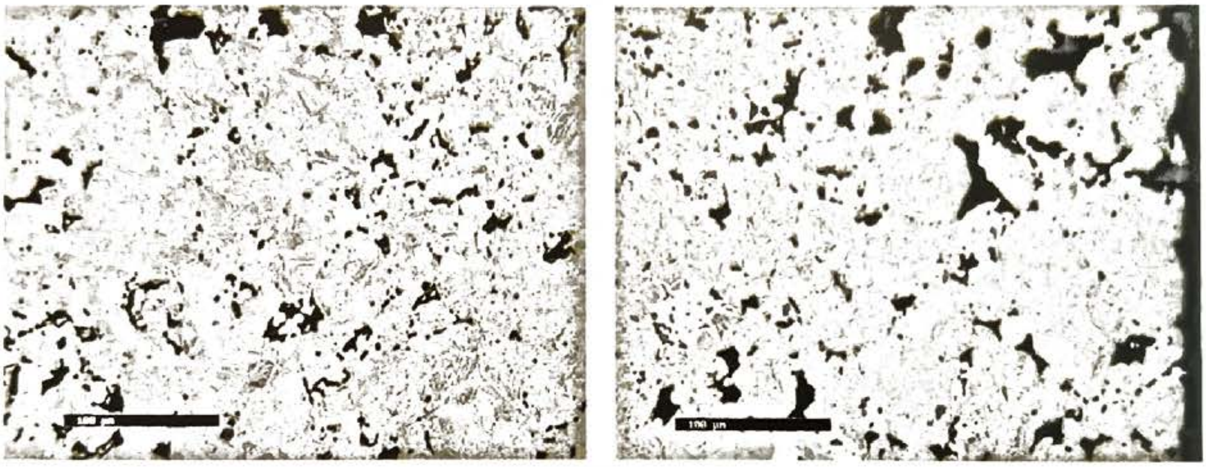
MANUFACTURING CONDITIONS: 0.8% Amide wax; P: 650 MPa cold compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), 20 min at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo + 1% Ni
650 MPa warm compaction (7.40 g/cm3), 20 minutes carburizing
Various graphite additions

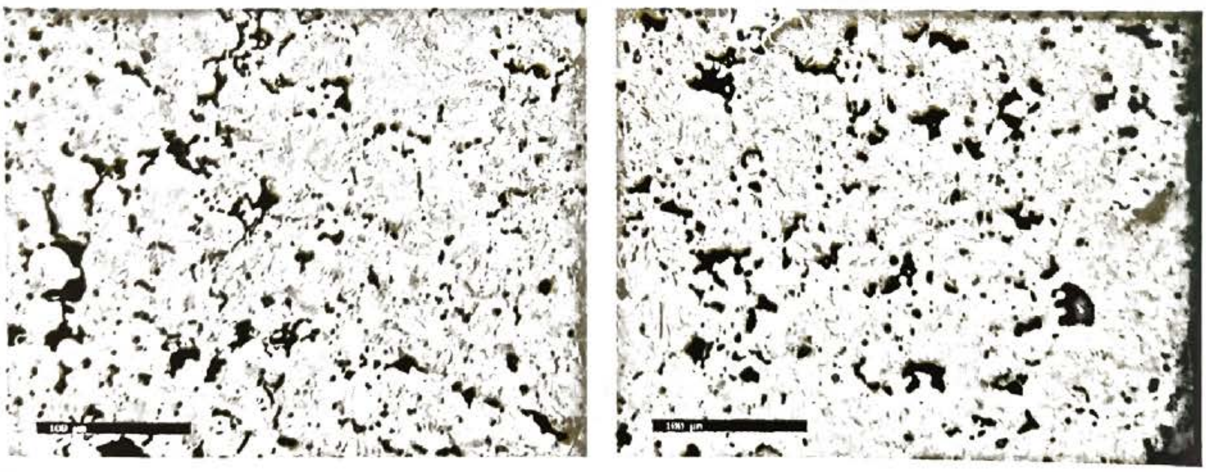
Centre | Surface



No graphite addition



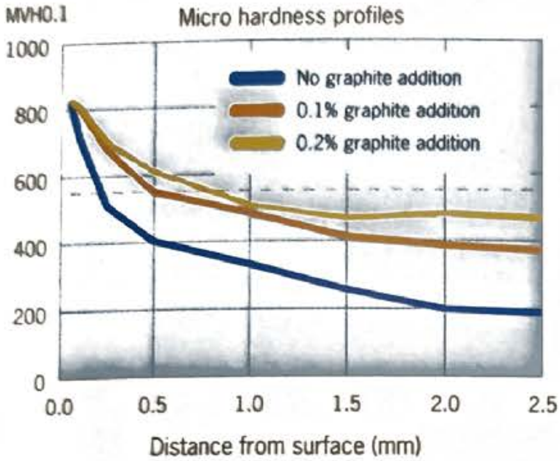
0.1% graphite addition

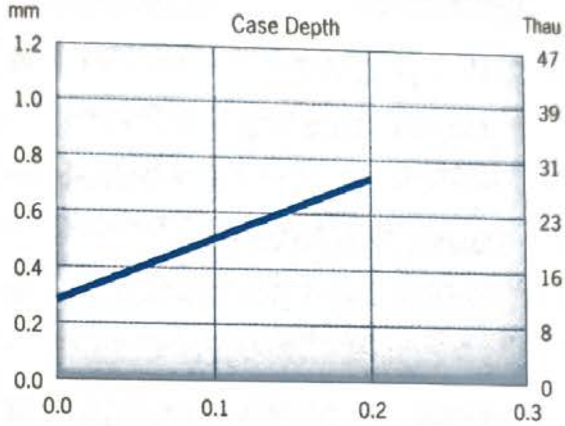


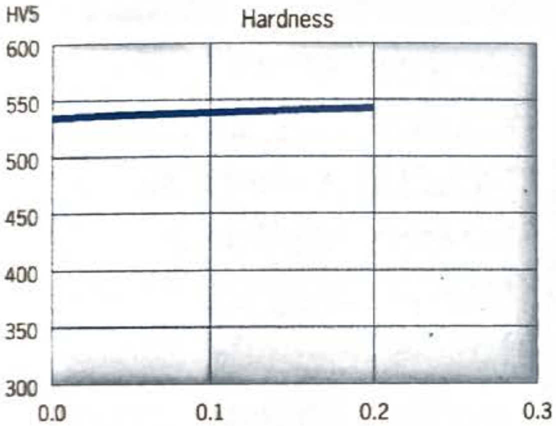
0.2% graphite addition

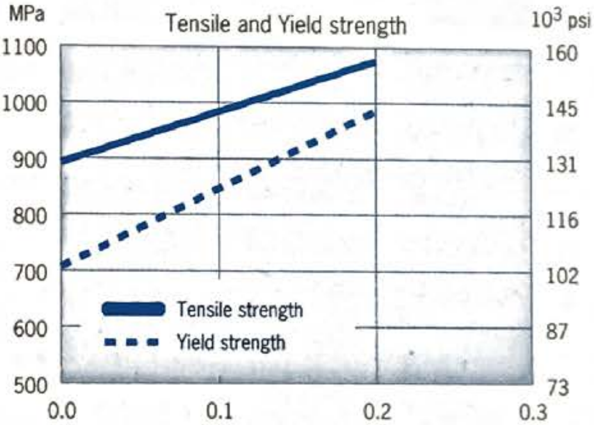
Astaloy 85 Mo + 1% Ni

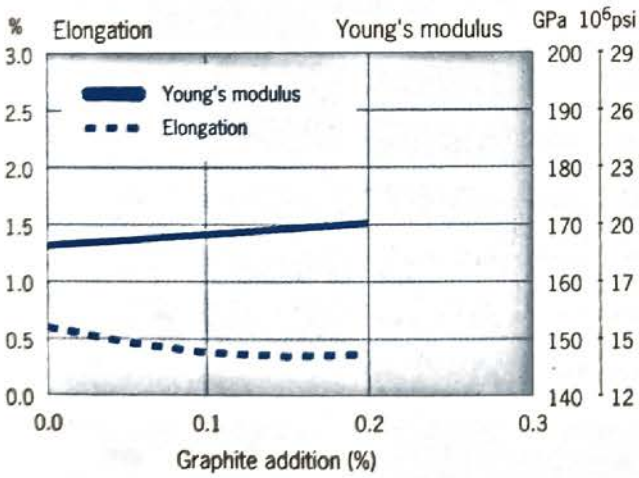
Case hardening

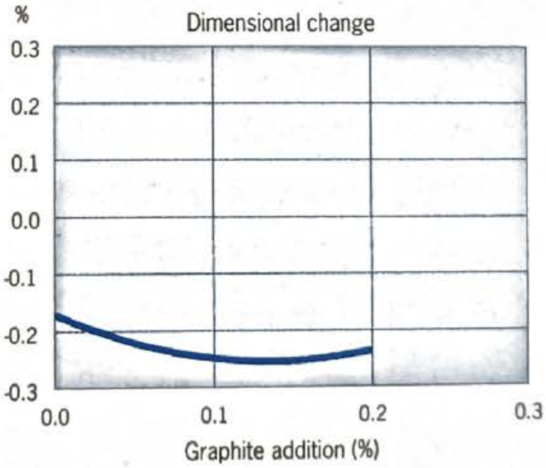








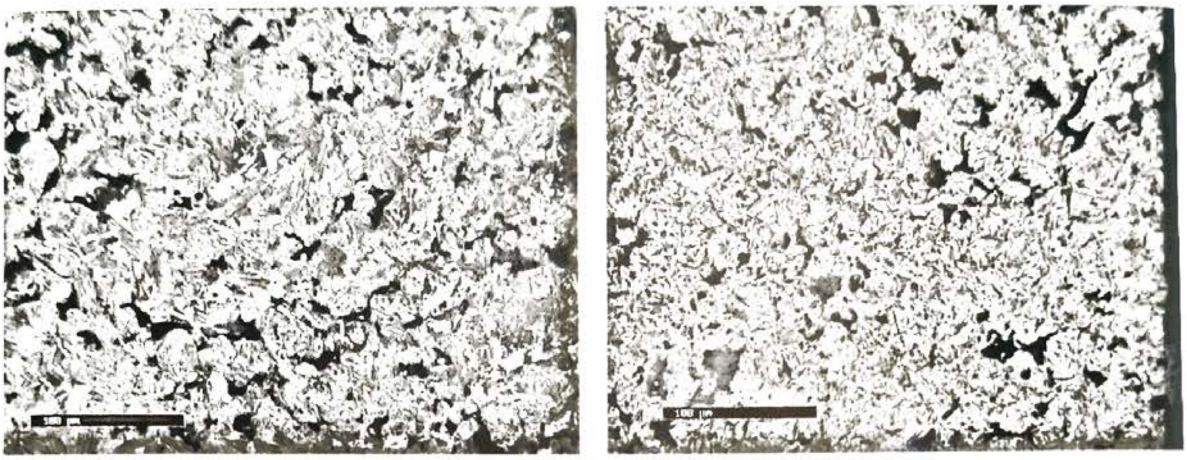




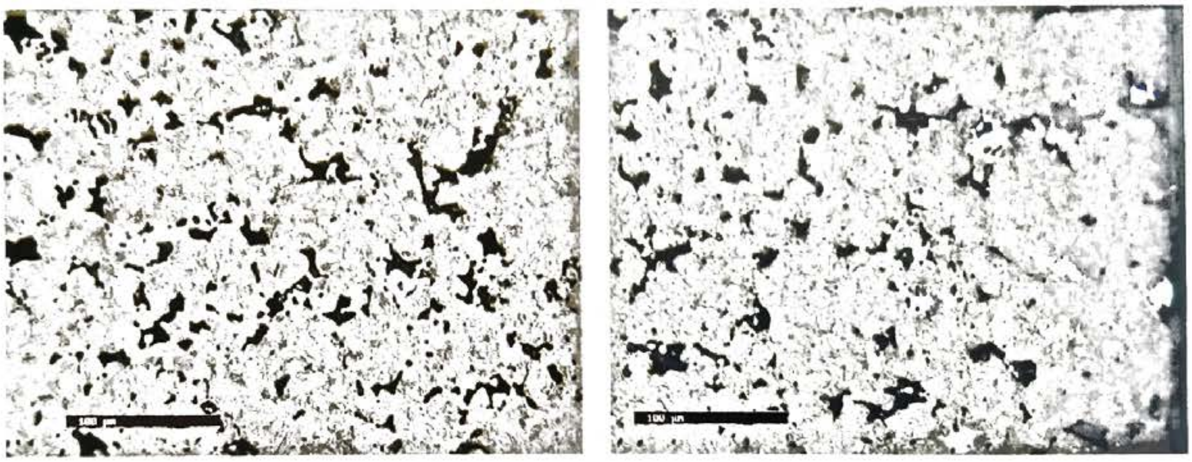
MANUFACTURING CONDITIONS: 0.6% Lube; P: 650 MPa warm compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), 20 min at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo + 0.1% Graphite
650 MPa conventional compaction (7.20 g/cm3), 20 minutes carburizing
Various nickel additions

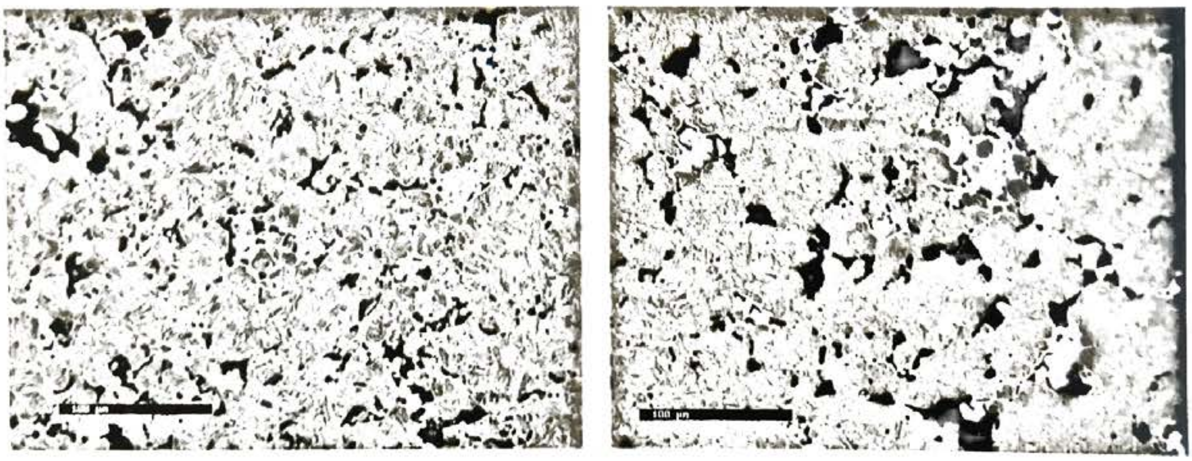
Centre | Surface



No Nickel addition



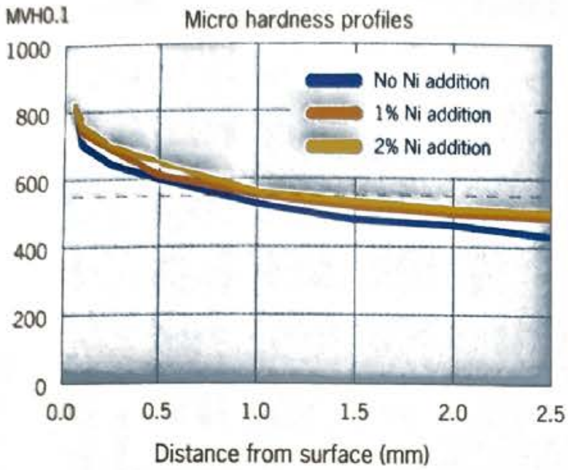
1% Nickel addition

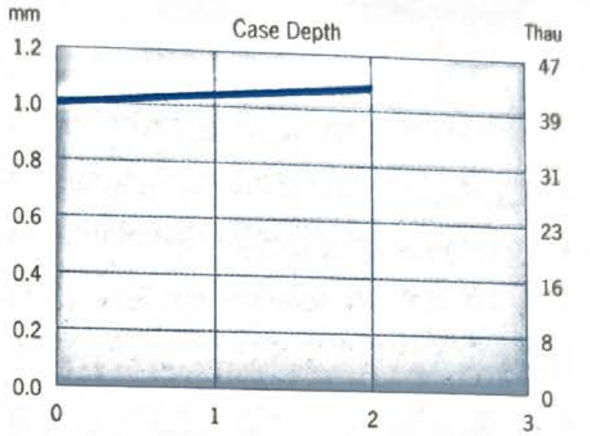


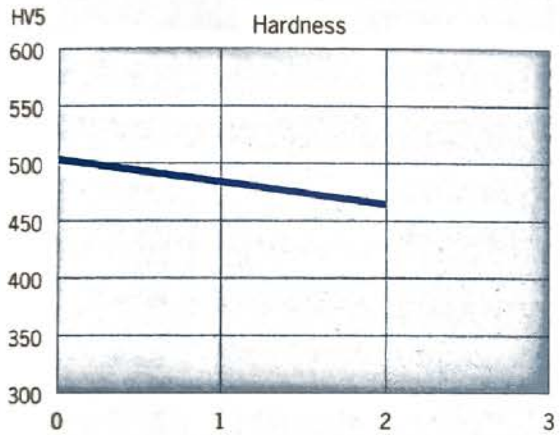
2% Nickel addition

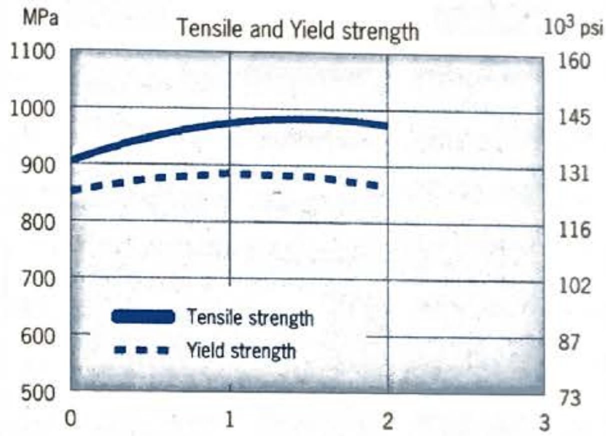
Astaloy 85 Mo + Ni

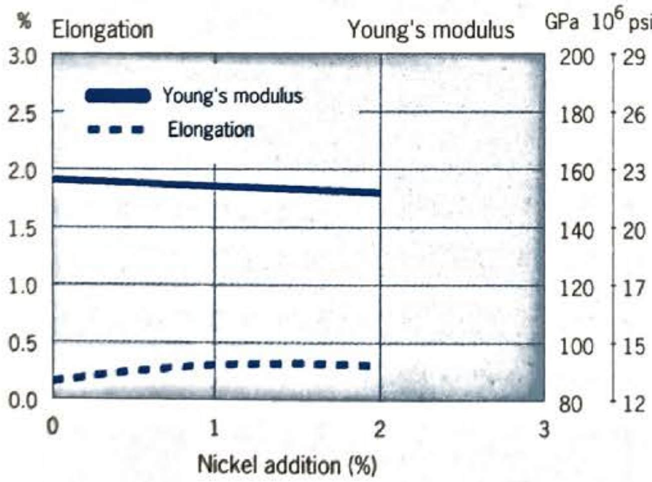
Case hardening

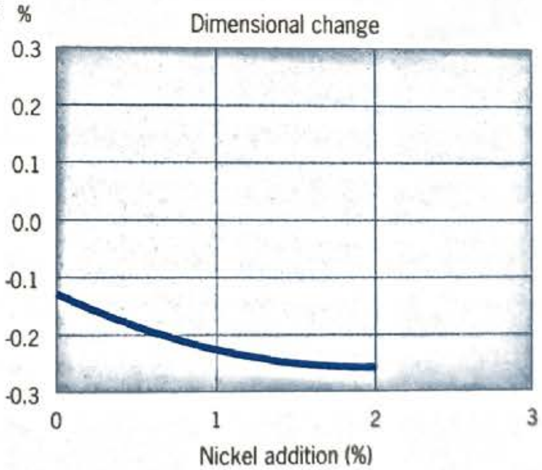








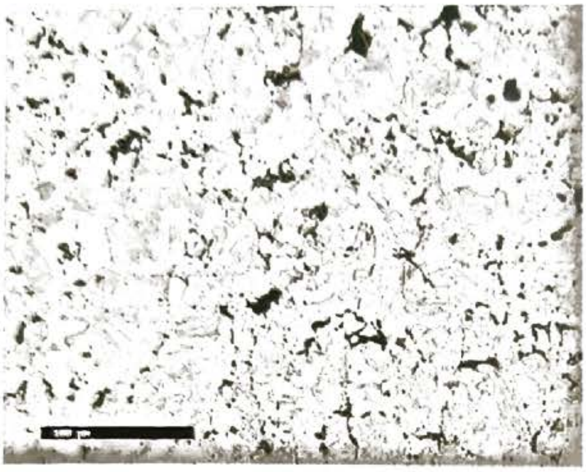




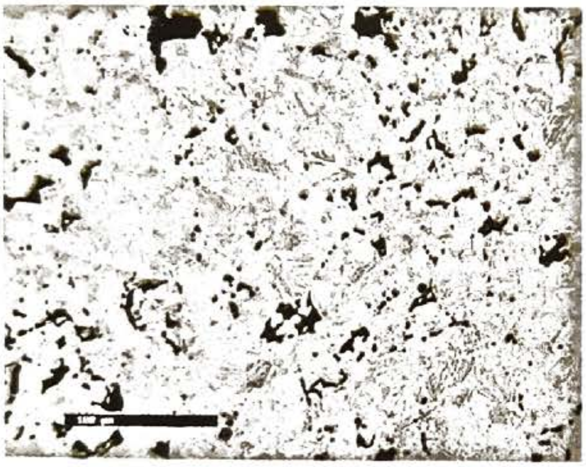
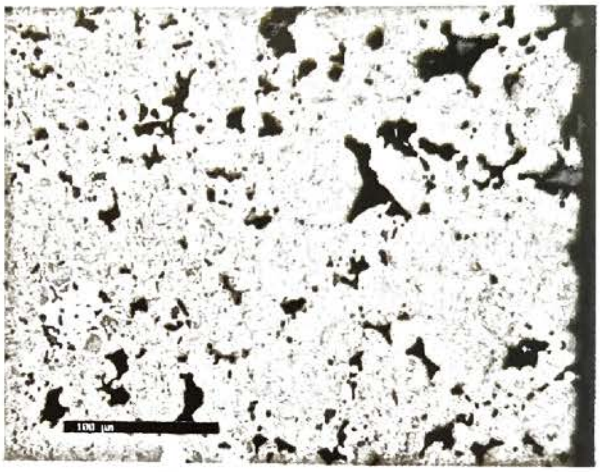
MANUFACTURING CONDITIONS: 0.8% Amide wax; P: 650 MPa cold compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), 20 min at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.

Astaloy 85 Mo + 0.1% Graphite
650 MPa warm compaction (7.40 g/cm3), 20 minutes carburizing
Various nickel additions

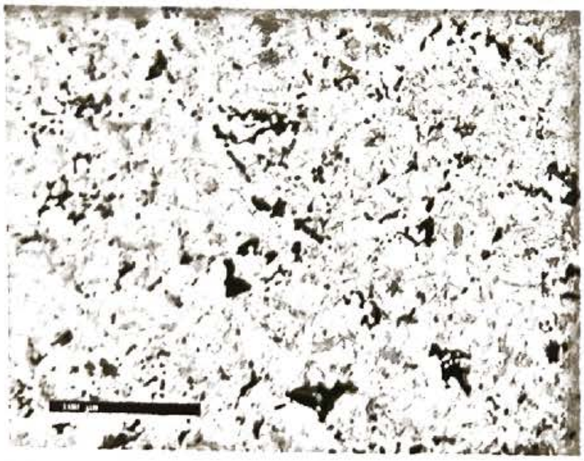
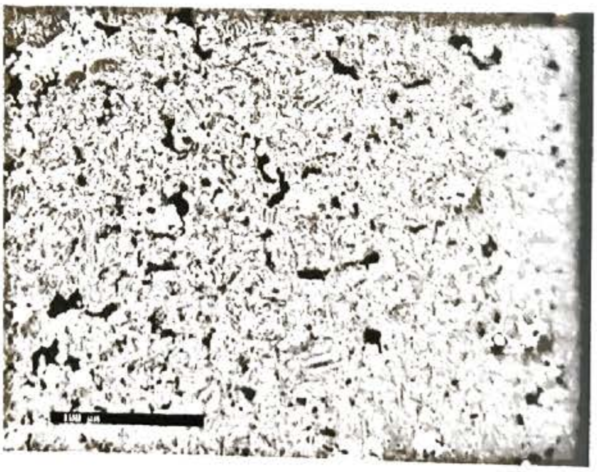
Centre | Surface




No Nickel addition

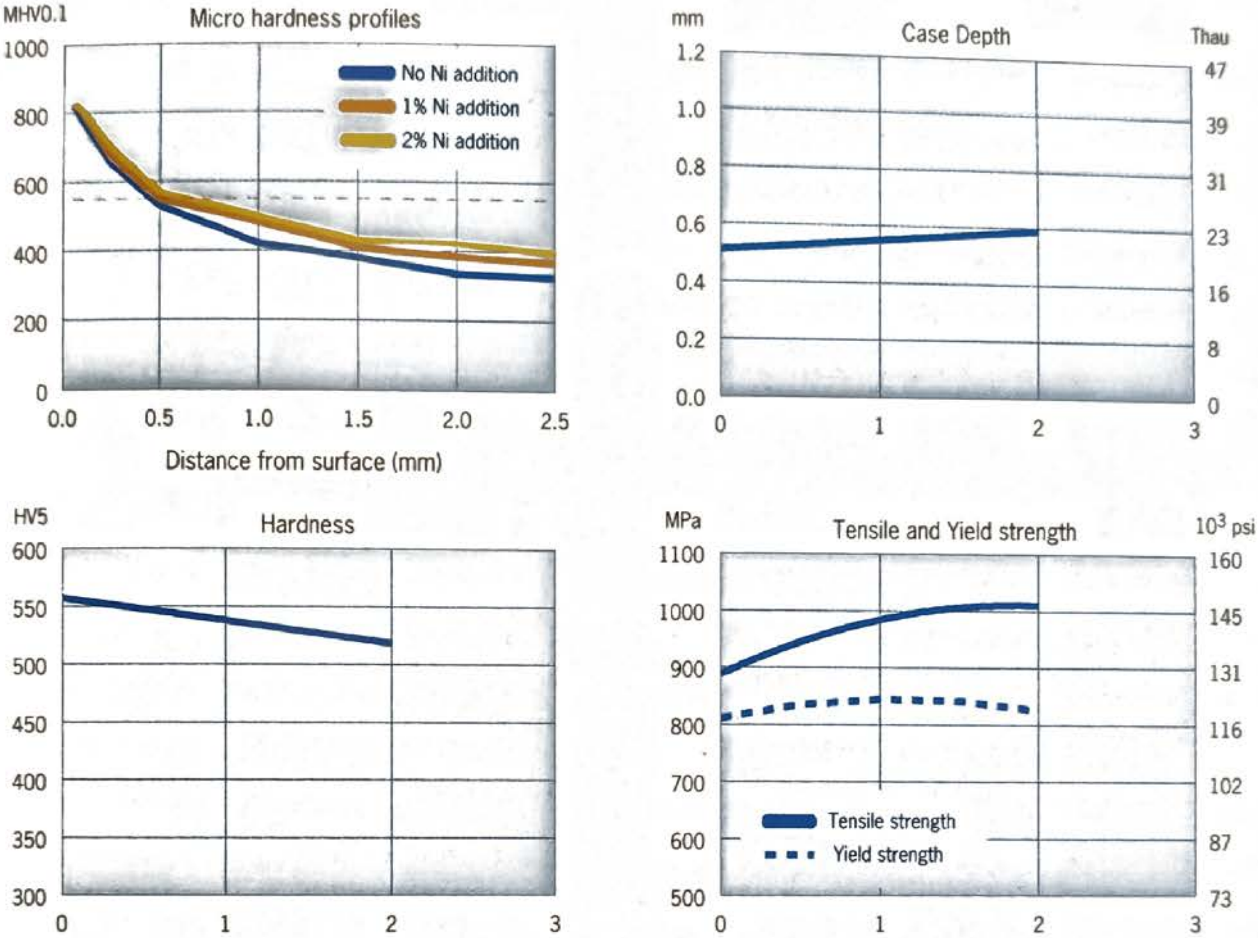
1% Nickel addition

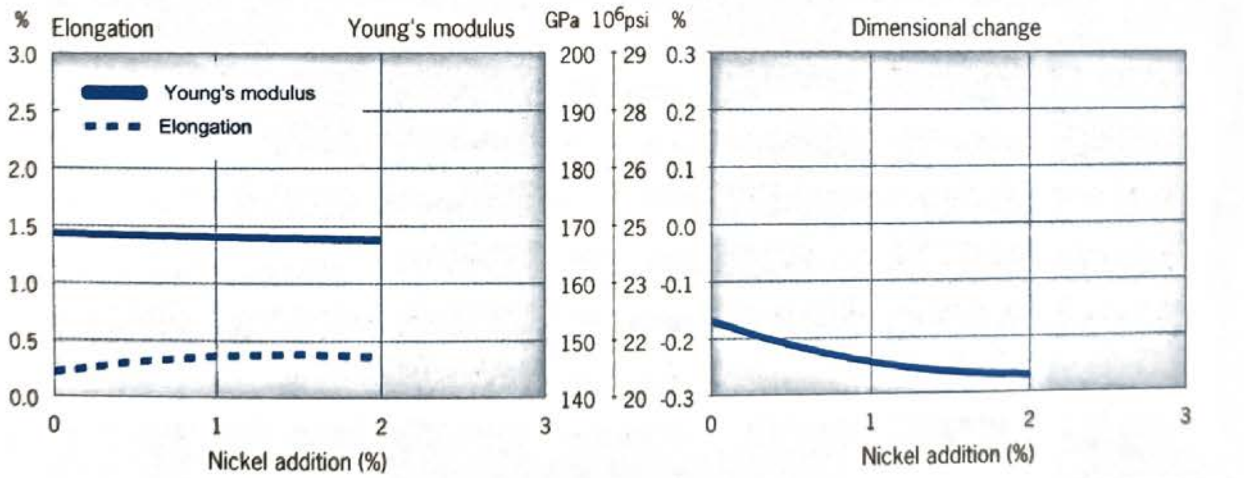



2% Nickel addition

Astaloy 85 Mo + Ni

Case hardening





MANUFACTURING CONDITIONS: 0.6% Lube; P: 650 MPa warm compaction; S: 1120°C (2050°F), 20 min in 90/10 N_2/H_2. Carburizing 920°C (1690°F), 20 min at 0.8% C-pot. Tempering 180°C (355°F), 60 min in air. Dimensional change: Green to as hardened.