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Tesi di Laurea Magistrale in Ingegneria dei Materiali

OTTIMIZZAZIONE DEL TRATTAMENTO TERMICO DI UNA GHISA MULTILEGATA CON GRAFITE LIBERA

STUDY ABOUT THERMAL TREATMENTS ON A MULTI-ALLOYED IRON WITH FREE GRAPHITE

£TUDE DU TRAITMENT THERMIQUE DôUN [illegible] AVEC GRAPHITE LIBRE

Relatore: Prof. Irene Calliari

Correlatori : Prof. Jacqueline Lecompte-Beckers
Ing. Jérôme Tchoufang Tchuindjang
Ing. Hakan Paydas
Ing. Olivier Dedry

Laureando: TOMMASO MAURIZI ENRICI

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1. Abstract

English version:

The research about the High Speed Steel (HSS) for Hot Strip Mill is moving to the opportunity of safe money decreasing the roll change with anti-sticking and lubricant properties; in the last year a composition was characterized to investigate the simultaneous presence of graphite, in particular spheroidal graphite, and a hard microstructure. The aim is to combine the hard martensite matrix, hard carbides coming from particular carbide-forming elements as vanadium and niobium, and spheroidal graphite nodules in the shell of a duplex material roll. The Marichal Ketin Industries with the University of Liège collaborate to arrive on this combination; a considerable amount of vanadium, silicon, molybdenum and niobium were granted for both the aim. In this work two compositions, coming from the evolution of a first trial, are investigated to evaluate the carbides presence to ensure a hard microstructure, verify the graphite shape evolution and the increase of the graphite amount to have the possibility of anti-sticking properties, investigate on the solidification steps to understand the causes of the structure formation and evaluate the effects of different thermal treatments on the HSS with free graphite. Thermocalc simulations, DTA tests and microscope surveys were carry out to analyze the microstructure; moreover Dilatometer tests, Magnegage analyses and Hardness tests were performed to investigate the behavior of the HSS in the different depths and to evaluate the influence of thermal treatments on the microstructure. The graphite was observed and evaluated into the microstructure together with all the carbides to understand especially the solidification steps and the possible behavior during the use of the HSS with free graphite.

French version:

Les aciers de coupe rapide de type HSS (High Speed Steels) ainsi que les fontes fortement alliées repr®sentent une ...ment utilisés comme cylindres de laminoirs dans les trains à bandes ¨ chaud, et particuli¯rement les bandes finisseus lôoxydation ¨ chaud, ainsi quôune ... cages des trains à bandes r®sistan finisseuses ont connu des d®veloppements avec lô® ¨ lôexception des derni¯res cages o½ on trouve t libre qui est essentiel pour assurer une bonne lubrificatio en cours pour lô®laboration dôun alliage de typ finisseuses. Un tel alliage comportant à la fois une matrice dure martensitique, des carbures de solidification r®sistants ¨ lôusure et form®s par des ®l®ments c permettre dôam®liorer le rendement des ... campagnes Marichal Ketin collabore avec lôUniversit® de Li¯ge p présente étude porte sur des matériaux ayant des compositions chimiques proches, de type HSS graphitique, qui ont été élaborés par MK avant dô°tre caract®ris®s au MMS. Trois c et elles sont obtenues en faisant notamment varier de manière plus ou moins significative des éléments tels que C, Ni, Nb, Cr, pour voir lô... solidification, la nature des ... tell carbures, la forme et la quantité de graphite, etc. En outre on réalise des traitements thermiques et on étudie leur influence sur le graphite libre, et sur la teneur en austénite résiduelle. Différents outils et méthodes dôinvestigation sont utilis®s dans cette ®tude, t les analyses par ATD et dilatométrie, les caractérisations de la microstructure en optique et en microscopie électronique à balayage, les essais de duretés, les analyses avec jauge magnétique. Les résultats des différentes investigations sont discutés et des corrélations sont établies. La caractérisation du graphite dans la microstructure permet de comprendre les étapes de la solidification et du dégager les perspectives pour lôutilisation du HSS graphitique dans le cadre de

Italian version (large version):

La ricerca riguardo gli acciai rapidi (HSS o High Speed Steel) per laminazioni a caldo si sta muovendo verso lôoppor risparmio di denaro, diminuendo il cambio di rulli da laminazione con proprietà di anti-attacco e di lubrificazione; nellôultimo anno un simultanea presenza di grafite, in particolare grafite sferoidale, e una microstruttura dura. Lo scopo è il combinare una matrice dura di martensite, carburi duri provenienti da particolari elementi formatori come vanadio e niobio, e noduli di grafite sferoidale nella parte esterna di un materiale duplex per rulli . Lôindust Marichal Ketin con lôUniversit¨ di Liegi collabor quantità di vanadio, silicio, molibdeno e niobio sono utilizzati a questo scopo. Marichal Ketin grazie alla continua innovazione ha avuto nellôultimo secolo una posizione laminazione di qualità, sia per le avanzate tecniche di produzione, sia per lôelevato cont specifiche classi di materiali per le laminazioni a caldo (Hot Strip Mills o HSM). Attualmente la produzione è portata avanti con il processo di colata centrifuga (Centrifugal casting), capace di produrre un ampio range di ICDP (Indefinite Chill Double Poured Cast Iron), Enhanced ICDP, HiCr Iron (High Chrome Iron), HiCr Steel (High Chrome Steel), SHSS e HSS come materiali esterni in rulli duplex da laminazione. Questo processo insieme a specifiche procedure d, ottiene produz grande precisione sulla struttura del materiale, possibilità di produrre rulli duplex e assicurare una finitura superficiale ottima. Le forze centrifughe e uno studio della solidificazione consentono un legame metallurgico tra il materiale esterno (ñ shell) e materia (ñ core necessario per assicurare unôelevata qualit¨ nel tenace e di solito è ghisa grigia o sferoidale, mentre il materiale esterno duro con unôalta resistenz Negli anni si è tentato sempre di migliorare le proprietà dello strato esterno per migliorare le prestazioni generali del rullo; lôuso di costosi elementi for come i carburi MC, quindi tentando solo di incrementare la durezza superficiale del rullo da laminazione. Le elevate forze e le ampie superfici di contatto presenti nelle passate finali di laminazione però hanno sempre portato a fenomeni di attacco delle superfici e di conseguenza molti incidenti durante lôutilizz Questo attacco tra le superfici porta a prodotti di laminazione con una finitura superficiale scarsa e possibilità di cricche per gli stress residui. La classe HSS, rispetto a tutte le altre tipologie, ha mostrato le migliori prestazioni come proprietà di anti-criccatura e anti-attacco, ma gli incidenti sono frequenti e continue interruzioni dovute al cambio dei rulli non sono Come già detto in precedenza al momento la ricerca si sta muovendo per dotare il materiale esterno di rulli duplex di proprietà lubrificanti intrinseche e di anti-attacco; la presenza della microstruttura e le sue proprietà correlate sono già conosciute. Le possibili nuove proprietà del metallo date dalla presenza di essa sono state verificate accompagnate a durezza superficiale e resistenza ad usura. Durante lo scorso anno una prima composizione è stata caratterizzata, essa presentava una microstruttura dura e grafite sferoidale; per arrivare a questa combinazione è stato utilizzata una considerevole quantità di vanadio, silicio, molibdeno e niobio per ottenere entrambi. Alcune analisi vennero effettuate su questo primo tentativo a tre distanze differenti dalla superficie (10, 25 e 40mm) per valutarne le caratteristiche; analisi Thermocalc, analisi DTA e rilevazioni al microscopio sono state effettuate per valutarne la microstruttura. La presenza della grafite è stata verificata ed accompagnata da alcuni carburi: carburi primari MC, carburi euttetici M_7C_3, carburi eutettici M_2C e carburi secondari M_xC_y. In questo studio due composizioni, provenienti dallôevoluzione di un primo tentativo assicurare una microstruttura dura , verificare la formazione e lôincremento del q grafite per assicurare la possibilità di proprietà di anti-attacco, studiare le fasi di solidificazione per capire le cause della formazione di una particolare struttura e valutare gli effetti di diversi trattamenti termici sul HSS con grafite dispersa. Il primo test effettuato è la simulazione Thermocalc in condizioni di equilibrio e pseudo-equilibrio per avere unôindicazione delle po composizione; questo test in particolare sar¨ uti

Liquidus e quindi sulla temperatura massima da i
dell’HSS. Per studi aerlel al ag rvaafriitaez isofneer odiid aflœrmaal lđô a
diversi trattamenti termici si è utilizzato un microscopio ottico su vari campioni trattati con diversi trattamenti termici: campione (prima composizione) trattato termicamente con doppia tempra a 530°C in 24h (campione X), campione X trattato successivamente con una reaustenitizzazione a 1025°C/1h (campione R1), un campione (seconda composizione) non trattato termicamente (N0) e due campioni trattati termicamente con due diverse doppie tempre partendo da N0. Oltre alle imma
della grafite sia per quanto riguarda la quantità sia per la forma, si è utilizzato il software Stream Analysis per valutare esattamente questa evoluzione nella lunghezza totale del campione per ogni millimetro. Per valutare esattamente e per confrontare la microstruttura rispetto al primo tentativo di composizione si è utilizzato insieme analisi DTA con due diverse temperature massime e osservazioni con il Scanning Electron Microscope. Si è utilizzato prima come temperatura massima 130
e successivamente 1450°C (temperatura massima durante il casting del materiale) per determinare possibili differenze tra i due test; le osservazioni con il SEM sono state effettuate prevalentemente alle stesse distanze delle prove DTA per abbinare ad ogni picco dello spettro una fase della microstruttura. Ulteriori osservazioni al SEM sono state svolte sul campione X e sul campione N0 per valutare le possibili modifiche delle fasi dopo i test DTA e Dilatometro. Infatti test al Dilatometro con temperatura massima 1025°C, evitando la fusione del campione e quindi stando al di sotto della temperatura Solidus, sono stati effettuati per valutare i fenomeni legati al riscaldamento della struttura e in particolare i fenomeni legati alla grafite. Infine sui campioni X, R1 e N sono state effettuati i test di durezza (Vickers HV 30) e valutazione della austenite residua con il Magne Gage per valutare la variazione di queste caratteristiche per le due differenti composizioni, a più distanze dalla superficie e con diversi trattamenti termici. Dalle analisi precedenti si è potuto valutare la composizione e la morfologia dei carburi già presenti nel precedente studio; il vanadio e niobio in particolare sono stati rilevati nei carburi MC. I carburi M_7C_3 sono stati osservati in due diverse morfologie in accordo con la microstruttura circostante e con la stessa composizione chimica; i carburi M_2C invece si presentano solo nella morfologia regolare complessa ed ¯ importante
silicio e molibdeno in essi. Attraverso le analisi DTA, le osservazioni al SEM e i test al Dilatometro (in particolare per l’effetto Budding, l etgato psosibile alla
ricostruire la sequenza di solidificazione e capire la correlazione tra la formazione della grafite e la formazione dei carburi M_2C, che si formano dallo stesso liquido dopo la formazione dei carburi M_7C_3. Si è rilevato, rispetto al primo tentativo, un incremento della grafite in superficie passando dal 0.7% al 2-3%. La sua forma tende ad essere sferoidale nei primi 35-40mm dalla superficie e mostra un aumento delle
ramificazioni tra i grani all’adunmeanftreddaemneto edaeulnala di
microstruttura differente, infatti l’HSS mostra
mostra una morfologia vermiculare o a scaglie dovuto al fenomeno del riscaldamento dopo la gettata del
ñmateriale’ôinternò dello stampo durante la getta
quattro distinte zone con quattro diverse microstrutture dove la solidificazione avviene con condizioni leggermente diverse, lasciando diverso quantitativo di liquido o uno spazio differente alla nucleazione e accrescimento della grafite e del carburo M_2C. Le zone, e quindi le microstrutture, vicino alla superficie tendono a lasciare più spazio tra i grani e liquido favorendo una crescita igroscopica dei noduli di grafite. Osservando questa evoluzione della grafite si è quindi provveduto a simulare i possibili trattamenti termici attraverso un particolare test DTA a tre step di riscaldamento e i test con il Dilatometro per verificare che effetti poteva avere la matrice supersatura in carbonio sulla grafite e viceversa e i possibili fenomeni del materiale. Si è riscontrato un continuo possibile movimento del carbonio dalla matrice ad altre fasi, tra cui probabilmente la grafite, gerafintpasreicondlareiadadfdh
carburi M_2C, insieme con la formazione di carburi secondari M_6C. Le conseguenze dei diversi trattamenti termici quindi sono stati valutati sulle fasi e sulla struttura, notando che essi portano ad un ritardo delle trasformazioni di fase, in particolare la decomposizione della martensite che può indurre alla precipitazione dei carburi secondari M_xC_y più stabili. Infine è stata valutata la quantità di austenite residua e la durezza dopo

i diversi trattamenti termici negli stessi punti ed è stata ideata una funzione di prestazione per valutarle insieme; come risultato il miglior trattamento termico è la doppia tempra a 525-530°C, il campione dove si ha il minor quantitativo di austenite residua, caratteristica predominante.

Summary

2. Acknowledgments

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Ultima ma perché più importante ringrazio la mia famiglia per aver creduto in me anche quando non me lo meritavo, grazie per tutti i bei momenti passati insieme.

Dedicato ai miei genitori e a mio fratello Mattia

3. Introduction

3.1. Marichal Ketin Industries and the research

This project takes its roots within the walls of Marichal Ketin Industries (MK) located at Liège. Since 1911, this company is one of the leaders in rolling mill manufacturing and Marichal Ketin casted the first European compound static roll in the 1951; still there is always a particular attention on the on-going innovation. The continuous research and developments had maintained this industry as one of the highest roll producers (as quality); the results of the most advanced technologies in casting, control and machining to roll manufacturing create specific roll grades for the Hot Strip Mills (HSM). Nowadays, the roll casting is done with the Centrifugal casting or rotocasting process; it is capable to produce full range of ICDP, Enhanced ICDP, HiCr Iron, HiCr Steel, SHSS and HSS roll shell materials. This process combined with specific procedure to regulate the solidification evolution obtains a high precision of the material, possibility to cast rolls with duplex material and ensure optimum roll barrel surface quality. The centrifugal forces and specific procedures ensures a metallurgical bonding betwe
necessary for an elevated quality in the successive manufacturing. The core material must be tough and usually is cast iron, meanwhile the shell material must be hard, with a high wear resistance. During years the layer part properties were improved and developed to achieve performances of the rolls; the use of expensive carbide-forming elements gave the opportunity to form h
HSS and semi-HSS are superior to the older grades for their smooth roll surface during rolling, especially in the middle-late stands.

3.2. New possible properties

The research until this moment went only to the direction to improve the carbide amount, thus only to increase the hardness; but the high forces and the high contact surfaces present especially in the middle-late stands of the manufacturing processes provide as consequence many incidents and problems bonded with the sticking of the surface. That sticking can give a non-smoothed surface product and the possibilities of crack extending by the compressive residual stress. The HSS shows better performance of anti-cracking and anti-sticking properties but the incidents are common and frequent interruptions due to the roll changing are not desirable to reach a high rolling productivity; farther the grinding is an outstanding cost for an industry. Nowadays the research is moving to diminish the roll changing in those stands maintaining the same hardness level and results level. The aim is to combine the hard martensite matrix, hard carbides coming from particular carbide-forming elements as vanadium and/or niobium and spheroidal graphite particles in the shell of the duplex material. The graphite presence inside a metallic matrix is already known and the properties bonded to it are also known. The high anti-sticking and lubricant properties of the metal coming from that presence were verified but accompanied with weak performance as hardness and wear resistance.

3.3. First trial

The Marichal Ketin foundries invest and bet on this opportunities of safe money decreasing the roll changing and in the last year a composition was characterized to investigate the simultaneous presence of graphite, in particular spheroidal graphite, and a hard microstructure. To arrive on this combination a considerable amount of vanadium, silicon, molybdenum and niobium were granted for both the aim. Analyses were done to a first composition at three different depths (10, 25 and 40mm) to investigate the characteristics; Thermocalc analysis, DTA tests and microscope surveys were taken to analyze the microstructure. The graphite presence was found together with several carbides in a martensitic matrix: primary MC carbides, eutectic M_7C_3 carbides, eutectic M_2C carbides and secondary M_xC_y carbides.

3.4. Current trials

The current study is about the next compositions to evaluate again the carbides presence to ensure a hard microstructure, verify the graphite shape evolution and the increase of the graphite amount to have the possibility of anti-sticking properties, investigate on the solidification steps to understand the causes of the structure formation and evaluate the effects of different thermal treatments on the HSS with free graphite. Again Thermocalc Simulations, DTA tests and microscope surveys were taken to analyze the microstructure; moreover Dilatometer tests, Magnegage analyses and Hardness tests were taken to investigate the different behavior of the HSS in the different depths and to evaluate which consequence the thermal treatments can have on the phases. Two different compositions (Composition 1 and Composition 2) were available from Marichal Ketin plus the results from the first composition studied (Composition 0). The graphite was observed and evaluated into the microstructure together with all the carbides to understand especially the solidification steps and the possible behavior during the utilization of the HSS for the application in the Hot Strip Mills.

4. Bibliography

4.1. Rolls for hot strip mills

Since the industrial era the laminated steel or laminated metals are one of the most used and formed products, thus the lamination process has become even more important. The increasing technology knowledge has enhanced the types of process with more safety and control, but the rolls are the direct responsible for a high final product quality and then their progress is mandatory.

4.1.1. History and evolution of rolls

Before the early 80ôs the most diffused materials Poured Cast Iron), the High Chrome Steel (HiCr Steel) and the High Chrome Iron (HiCr Iron). European rollmakers developed those roll grades that are considered as first modern materials for lamination rolls; they have been introduced since then in most of the existing roughing stands of Hot Strip Mills (HSM) as well as into the early finishing stands of compact strip mills. Nowadays these roll types are still the standard grades in many HSMs in the world, but even increasing roughing mills in terms of cost/performance ratio, including higher throughput and product quality, have stimulated the rollmakers to develop new different materials. In the early 90ôs High-speed steel rolls (HSS) or s High speed steel rolls (semi-HSS) were introduced for the use in hot strip mills and gradually started to replace all the older grades for their superior wear resistance and the smooth roll surface during rolling. The ICDP was enhanced with the adding of MC carbides to have an improvement, but in comparison with the conventional ICDP it had only a wear resistance increase of the 1.2 to 1.5 times. The HSS rolls had much higher wear resistance (4 or 5 times) but they keep exhibiting manufacturing problems especially in the final stands. Today special HSS are studied to resolve these problems. [4, 7]

Figure 1 : A roll after heat treatment in Marichal Ketin Industry. [25]

4.1.2. Applications

The roll grade of ICDP and all the other roll types are used in many different layouts as Hot strip mills, Steckel mills (used for the stainless steel production), Plate mills, in Cold mills as work roll and Back up roll in Skin pass mills. In the same manufacturing can exist also many various example as full continuous hot strip mill with 5 to 7 roughing stands, three-quarter continuous hot strip mill (includes at least a reversing roughing stand and one or several one-way roughing stands), semi-continuous hot strip mill that combines one reversing roughing mill with a vertical edger and twin-tandem reversing roughing mill. All these applications need a high control of the performances and a smooth surface especially in the latest stands where the applied forces are higher. [5]

4.1.3. Commercial names

There are produced a few grades in the Marichal Ketin Indutries (MK) and their names depends on composition and on the kind of material used. The HiCr Iron is called COMET and it is stood out in based on the amount of carbon and chromium; the HiCr Steel is called GALAXY or GALILEO in based on their carbides amount and the possible applications. The HSS finally is called SIRIUS, KOSMOS or AURORA for their alloying elements amount and for the carbides presences in the matrix. All are used as work rolls and the main their characteristics are in the Table 1 (is placed also the normal produced ICDP to make a comparison with the other grades). [26]

	Tensile strength (MPa)	**Hardness (Vickers HV)**	**Best characteristics**	**Applications**	**Carbide amount (%)**
ICDP	350/450	500/730	SO, Sl	HSM, Steckel Mills and Heavy Plate Mills	35/45
COMET 90	700/800	500/800	WR, FC	Front finishing stands of HSM, Backup and work rolls for Hot Skin-pass Mills	25/30
COMET 70	600/800	390/680	WR, FC	Heavy Plate Mills and Hot Mill roughing stands (Steel & Aluminum)	20/25
GALAXY	700/800	500/730	WR, FC	Continuous and reversing roughing stands of HSM	8/10
GALILEO	700/800	500/730	WR, FC	Continuous and reversing stands of HSM and for Plate mills	/
SIRIUS	800/1000	580/690	WR, SO	continuous and reversing roughing stands of HSM and for Steckel Mill roughing stands	/
KOSMOS	900/1000	600/730	WR, SO	Early stands of HSM, Steckel Mills and Direct Strip Casting Mills	
AURORA	800/1000	600/730	WR, SO, FC	Early finishing stands of HSM (conventional and Minimill) and work rolls for Steckel Mills	/

Legend :
- ¶ WR= Wear resistance
- ¶ SO=Sticking-roll oxidation
- ¶ FC=Fire cracks
- ¶ Sl= Slippage

Table 1 : List of the principal MK compositions with the main characteristics [26]

The grades are placed in order to the Tensile Strength, the characteristics and the applications are similar for type of grade according to the hardness and the carbides amount (not all data are available).

4.1.4. Manufacturing by casting

There are many casting processes and their choice depends especially on the roll type and the materials use; they can be divided in static casting, spin casting and continuous pouring casting based on the characteristics.
The continuous introduction of new casting and p
pickling and continuous annealing lines gave a constant increase of the performances; the productivity and the product yield increased, tail-out roll defeats decreased and rolled steel quality was improved with the introduction of continuous processing lines. When defects like roll marks or heat streaks occur, the resultant damage increases at an emergency stop or strip breakage. Thus it is required to keep continuous lines operating in a steady and stable state. The rolled tonnage became dependent on roll surface roughening
texture or roll surface roughness loss and unti
manufacture of rolls of a thicker hardened depth by adding alloy elements that improve hardenability. As a result, the effective use of rolls diameter raised and many manufacturing rolls type were developed in that direction. [7, 10, 11]

4.1.4.1. Static casting

The static cast is the simplest possible casting system and it is a low cost manufacturing method. It is used for mono-structure rolls as Back-up and Structural rolls without special treatment or movement; the mould is prepared and the melt metal is injected in a specific procedure to control of the level, to regulate the solidification evolution and to ensure the optimum roll barrel surface quality. Each mould design incorporates massive barrel and bottom neck chills, resin bonded sand top necks and insulated feeder heads together with an integral bottom pour runner and ingate system. These designs ensure rapid solidification rates in the roll barrel while maintaining the best possible liquid metal feed during roll solidification. The pouring system incorporates a tangential ingate to provide smooth clean metal flow with minimum turbulence during mould fill. [27]

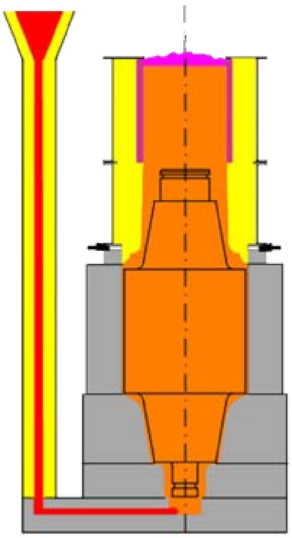


Figure 2: Structure of the static casting. [27]

4.1.4.2. Horizontal static cast

The horizontal static casting is composed by a spin casting of the external shell and a static casting of the core; this type of cast is used for mono and complex structure rolls with materials higher alloyed than the static cast ones. In the first the chill mould is placed horizontally in a centrifugal casting machine and the horizontal axis of the mould is putted on rotation, then the melted shell metal is poured inside of it and the rotation is maintained until the stability of the shell. The mould is moved and it is brought in the vertical position with inside the solidified shell but still at elevated temperature (rotated through 90°C). The perpendicular axis chill section is placed onto a bottom refractory lined neck box as a part of the mould assembly procedure and then the top refractory neck box is placed into the upper position ready for the introduction of the core metal. In the final step the liquid (tough core) metal is poured under control from the bottom part of the composed mould; the core metal has to fill in the central part of the roll (where there is also the shell) and the two peripheral parts (necks). [29]

4.1.4.3. Centrifugal casting

The centrifugal casting or rotocasting is one of the newest castings and MK use that process for their alloyed rolls with duplex material; it is possible to produce a full range of ICDP, Enhanced ICDP, HiCr Iron, HiCr Steel, SHSS and HSS roll shell materials with this casting. Computerized technology combined with rigidly defined specifications and procedures ensures that the highest level of process control is applied to every cast. The use of a vertical spin casting process combined with a single piece chill containing the roll barrel and necks allows for the entire roll to be cast in a single, continuous operation with minimal delays between steps, thereby ensuring the highest degree of control and consistency. The shell is usually made up with a hard material, both wear and thermal resistant, while the core and the necks are made up with a ductile and

toughness material. The process can be divided i
due to the shell casting the pouring nozzle is not straight but is placed with an angle among vertical axis. When the melt metal is poured the spout puts it directly in the mould shell space; the results are the perfect filling of the shell space and a little excess of shell metal in the lower part of the mould shell space due to the centrifugal force field and due to the shape of the nozzle as shown in Figure 3. [28]

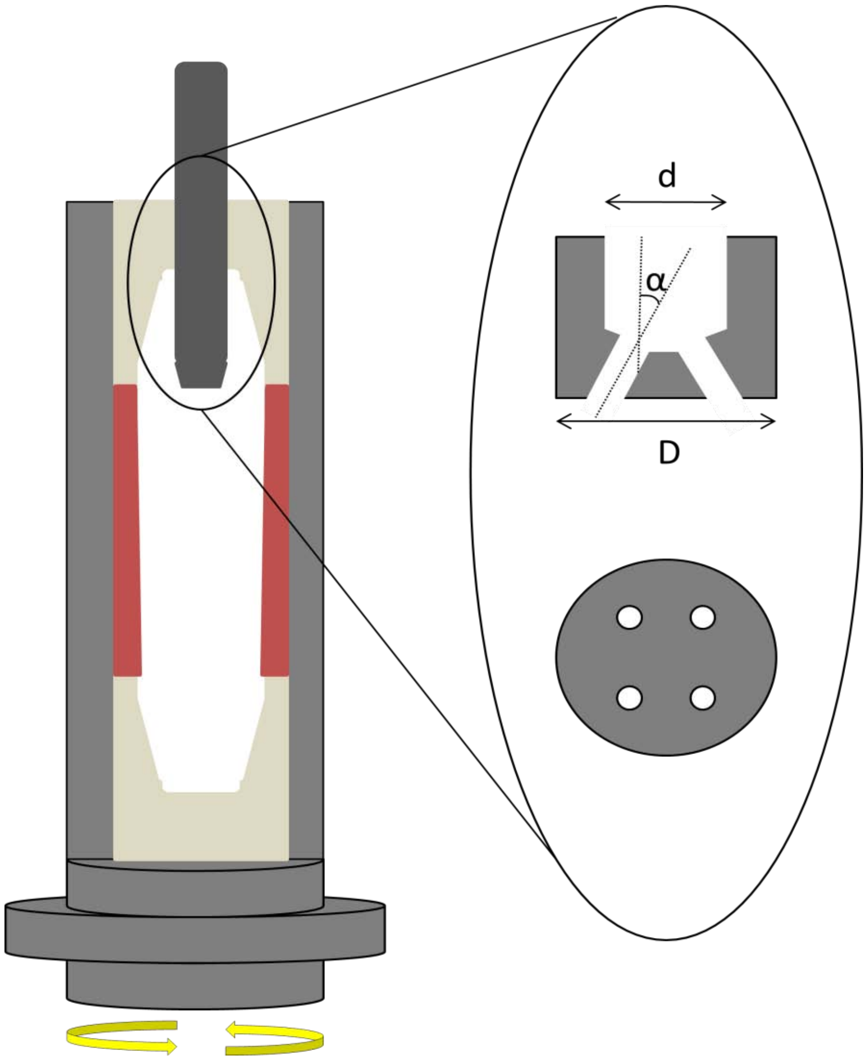


Figure 3: The centrifugal casting structure, with a focus of the casting nozzle on the side view and the bottom view.

When the shell metal is stable (usually it needs four minutes and still at elevated temperatures) the melt core metal can be injected to fill in it; in this same step the necks (called also journals) are also casted. The rotation applied by the spincaster is higher in the shell step (600 rpm) and during the filling is wound down gradually. The spincaster can rotate from 300 to 3000 rpm. The mould contains sand pieces whose job is providing their shape to the journals and is closed by two plates. Exceptional care is taken during the spin casting process to ensure that the integrity of the interface between the shell and core material will withstand the varying forces generated during the roll service lifetime. After all the steps the mould with the roll inside is taken out of the spincaster and puts at rest for cooling; it needs one week to reach a temperature below 100°C as we can see in the Figure 4. The casting is usually a fine-grained casting with a very fine-grained outer diameter, owing to chilling against the mould surface. Impurities and inclusions are thrown to the surface of the inside diameter, which can be machined away. [24]

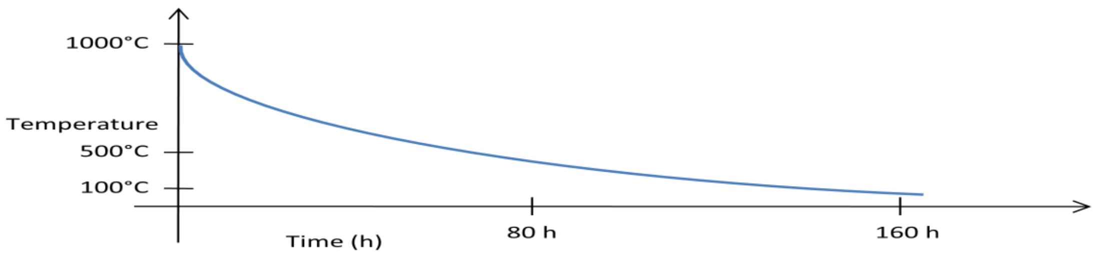


Figure 4 : Time scale of the cooling process. [24]

Centrifugal casting was the invention of Alfred Krupp, who used it to manufacture cast steel tyres for railway wheels in 1852.

4.1.4.3.1. Homogeneity of metallographic structure

In the centrifugal casting strong centrifugal forces are applied and segregation during solidification is likely to occur with this process due to their. Whether visible clear segregation can be found on roll surface, its pattern may be transferred to the rolled strips when the rolls are used in the last stand, which may lead to severe quality problems. Two of the typical segregation patterns observed on the roll surface of centrifugal cast rolls are called ñcat marksò and ñsegregationò, one corresponds to a few millimeter-sized round spots appeared all over the roll surface, which correspond to matrix distribution worn preferentially, consequently recognized as craters or pits. The second one observes the cross section view at the corresponding part of the roll, laminated segregations composed with different microstructure size layers are found. From the roll surface, boundaries of the laminated layers appear as segregation. These types of segregation are formed by a combination of manufacturing and material conditions such as cooling rate, pouring speed, pouring temperature, density of molten metal and molten metal movement in a centrifugal force field. These conditions need to be critically controlled for each roll material in order to achieve homogeneous metallographic structure. [4]

4.1.4.4. Continuous Pouring process for Cladding (CPC)

The CPC process is a centrifugal casting concurrent for the manufacturing of new composite rolls. Alloy additions are not limited substantially in the casting of HSS materials, the solidification and cooling rates are high, a fine cast structure is obtained with solidification progressing from the surface toward the center or in the radial direction of the roll. The casting is vertical as the spin casting but the core is cast before the shell. The molten shell metal is poured into a gap between the vertical core and the water-cooled mould arranged concentrically with the core.

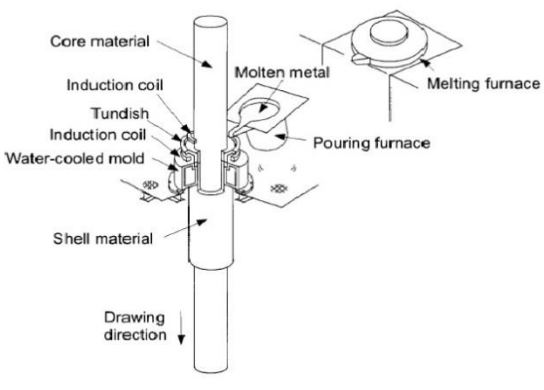


Figure 5 : Schematic drawing of a CPC process. [11]

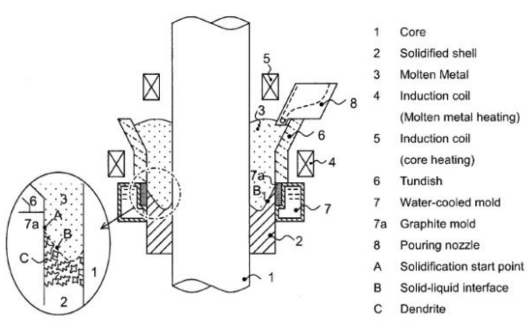


Figure 6 : Continuous pouring process for cladding (CPC). [11]

The shell is progressively solidified to be tightly bonded with the core and is intermittently downward to form roll. During the shell solidification the front basically moves in the radial direction of the roll or in the horizontal direction. To ensure the connection between the two materials two different induction coil are present to heat the connection zone of both parts, but to give a high connection in many rolls another intermediate layer of different composition is obligatory and thus more steps or a more complicate casting are necessary unlike the centrifugal casting. [10, 11]

4.1.5. Properties required for the rolling mill rolls

The rolls for roughing stands must have some specific properties to be considered adapt for the mill demands:

- **High shell resistance against wear, thermal fatigue and oxidation/corrosion; a homogeneous wear resistance allowing longer rolling campaigns and reduced downtime**
- **High fire crack and heat resistance**
- **High roll bite based on high friction coefficient is maybe the most important characteristic because it allow high reductions per pass without chattering or slippage, thus high throughput with reduced heat loss of the product**
- **Perfect roll surface quality over long runs; that is related to no peeling, no banding and no microspalling**
- **High safety against roll failures**

The ways to improve the characteristics usually are having lower carbide content but harder and no network of carbides, with those the shearing resistance and the absence of micro-spalling is enhanced. [7]

4.1.6. Problems in the manufacturing

During the manufacturing the later stands have the highest applied forced on the metal piece at the enhancing of the applied deformation and the highest manufacturing velocity due to the process. The deformation in a hot condition (hot lamination) is not the best way to consider the real process conditions, the deformation velocity ȳ is better in comparison with the V_r: norma

$$- \frac{ЎΩ}{ΏΩ_{ȿ}} \quad (1)$$

Equation 1: Deformation definition with Ўі іᵧH і ε [22]

$$ʘ \; \frac{ώ}{ΰ} \; ì \; î \frac{ΏΩ_{ȿ}}{ΏΩ_{ȼ}} \quad (2)$$

Equation 2 : Deformation velocity definition; where the final value of the interested dimension (thickness in our case) is ▌ the initial value of the dimension is ▌ε, the difference of values is Ў▌and L is a parameter of work [22]

The applied pressure and the force can be correlated directly with the desired deformation velocity:

$$ΰ̃_{ȁ\,ȷ} \quad \frac{ς\,ő}{Ӣσ\;ά\quad ρ} \; ϽȻ \; Ͻ\,ρ \quad \frac{‘\;ΰ}{ςΏΩ_{ȁ\,ȷ}} \quad (3)$$

$$ΏΟ \quad ΰώ\,ΰ̃_{ȁ\,ȷ} \quad (4)$$

Equation 3: Average pressure where C and m are referred to the mechanical properties of metal piece, the applied deformation velocity is Ǫ▌, the friction coefficient is Ҷand the average value of the difference of the desired depth is ▌ₒ [22]

Equation 4: Relative force in a lamination process where W is the width of the worked piece. [22]

The deformation velocity in the Equation 3 has the higher contribution to the pressure and force (as shown in the Equation 4) varying and at the decreasing of the $\dot{\varepsilon}_s$ (later stands in a manufacturing work) the deformation increases, as the Equation 2 explains. The velocity of the rolls has an important contribution in the Equation 2 and thus for the industry habit that wants high production and high velocity means higher values of deformation on the material. The applied pressure and the force in later stands have to be higher to arrive at high reduction and then the rolls have to support it. For these reasons rolling incidents tend to occur more frequently in HSM later stands; the typical roll incidents are the wear of the surface due to the high pressure or the cobble incident due to sticking. The first one is a normal consequence of rolls use due to the contact between two metals of different hardness and the second one is the worst possible accident because it compromises suddenly the manufacturing quality instead of the previous. [4, 22]

4.1.6.1. Cobble incident

The cobble incidents are due to the concentrated contact stress between the backup roll and the work roll at the adhered strip, in this area strip steel may stick to the roll surface. That aspect can give in the same time non-smoothed surface products and the possibilities of crack extending by the high compressive residual stress (when the crack forms some angle between the perpendicular line of the roll surface). The HSS in later stands shows inferior anti-crack and anti-sticking behavior in comparison with the old or enhanced ICDP and thus the latest is the widely used material in the later stands of the finishing train. The HSS has the advantage to have a higher wear resistance and then less need of grinding. Usually, there are 7 stands in which the earlier are with HSS and the latest ICDP in a standard HSM; the HSS can arrive to achieve over 5000 to 10000 tons of rolling without grinding, instead of the ICDP can achieve from 1500 to 2000 tons per each roll grinding (values without incidents). Frequent interruption of the rolling operation due to the roll change is not desirable in an effort to achieve the highest rolling productivity, farther the grinding is a high and relevant cost. [4, 5]

4.2. Materials for rolls

The materials used for the casting of the duplex material rolls can be very various; the hard shell part can be made up by materials considered steel, iron or cast iron and the tough core material can be various types of cast iron. In the first part the amount of the elements depending on the material can vary a lot, the carbon (C) can vary from 1% to 3%, chromium (Cr) from 1.5% to 11% and nickel (Ni) from 1% to 6%. For the iron materials those three main elements with the carbides formers give all the wear and hardness properties that the shell needs. The core materials usually are cast iron with different types of graphite (lamellar or nodular) with higher carbon amount (3-3.5%) and a completely different microstructure in comparison with the shell one.

4.2.1. Structure and microstructure

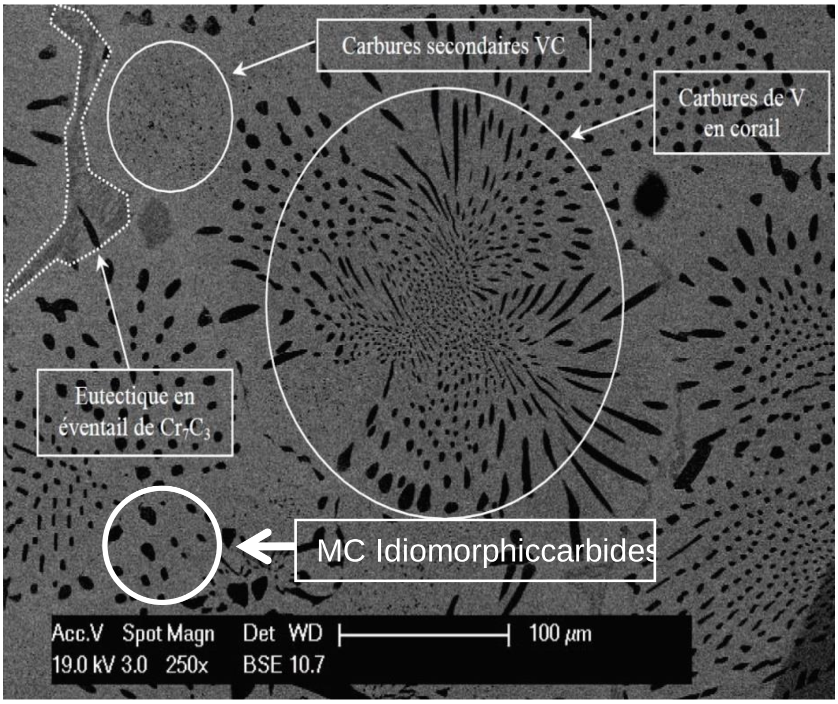
In the roll material for hot rolling, the alloys which dispense a large amount of carbide in the matrix are widely used because they are superior in abrasion resistance. High-alloy white cast irons, in which amount of carbides disperses in the hardenable matrix, are widely used for abrasion resistant parts. Steel strip mills are also one of their important application fields, through the durability of high-alloy cast iron rolls is superior to conventional low-alloy ones. The structure of the shell materials usually is made up to a hard martensitic matrix with a little amount of bainitic phase and dispersed carbides inside; the variety of it depends on the composition (total and local), the cooling rate and other phenomena during the casting. The core material is made up to cast iron with a matrix that can be pearlitic, ferritic or mixed and with a low percentage of cementite (<5%) to have a high toughness. [6, 8]

4.2.2. Carbides

The carbides role in the high alloyed metals is complex and variable. In general in the Fe-alloy the carbides have the tendency to precipitate in the intra-grain spaces and also are less present along the grain boundaries. Some carbides morphology has harmful consequences for the ductility for their fragility; nevertheless the carbides can give high enhancing of the break resistance, wear and abrasion resistance for their elevated hardness. The carbides are phases composed by carbon and various groups of ferrite stabilizer elements or iron; in low-alloyed steels the principal and in general simplest carbide is the cementite (M_3C) where the M is almost completely iron. Usually, this phase is present as ledeburite in the cast iron, a structure made up to perlite and that carbide. The cementite has lower hardness (800-1000 HV) in comparison with all the carbides and can give also fragility whether the amount is too high; the positive aspects of its presence are those which produce a uniform wear and a possible protective oxide layer whether the relatively low difference in hardness with the matrix is not too high. In high-alloyed steel to arrive to an enhancing of the properties, the intention is the variation of the ferrite stabilizer elements that can give harder eutectic carbides and with different morphologies in a martensitic matrix. The carbides that come from ferrite stabilizer elements can be divided in primary carbides that appears at high temperature with a possible precipitation from the liquid, eutectic carbides that appear at the eutectic temperature and secondary carbides that appear at lower temperatures with the possible precipitation through the solid phase. The primary and secondary carbides usually are placed inside the grain (intra-grain carbides) and the eutectic carbides in the grain boundaries (inter-grain carbides). An important general aspect of the carbides structure is that carbides must be well distributed and do not have to be with excessive dimensions; a continuous carbide network and then too much bonds between carbides must be avoided because it will be a help to the crack increasing and extending. Whether all those aspects are observed, the high-alloyed steels can have increased proprieties with a lower amount of carbides. [3, 6, 31]

4.2.3. Morphology

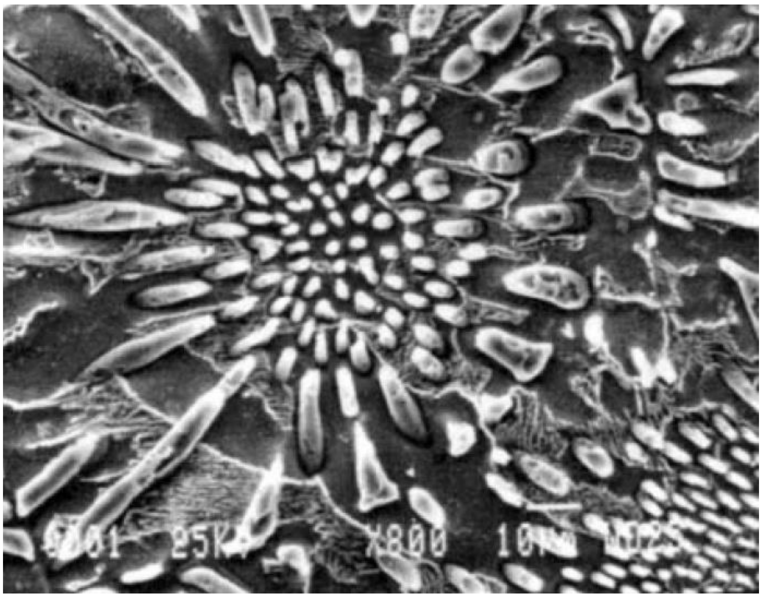
The carbides morphology is a huge and complex argument because a lot of variables like composition, cooling rate, carbides position and transformations can condition it.



Idiomorphic

Figure 7 : SEM figure of a general microstructure view of a low carbon steel (St37); idiomorphic MC primary carbides are present in the low left part, petallike MC carbide in the centre(called encorail in the figure), idiomorphic MC secondary carbides in the high left part and also a eutectic M_7C_3 carbide. [16]

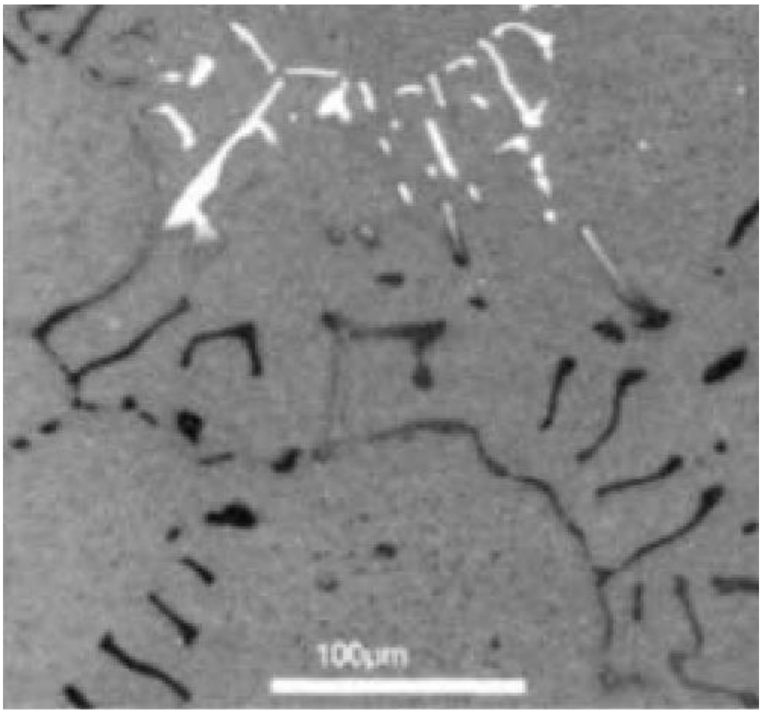
The idiomorphic is like isolated massive carbide and usually is typical of the primary carbides.



Petallike or Fibrous

Figure 8 : SEM figure etched to expose the eutectic phases; Fe-V-C system. [3]

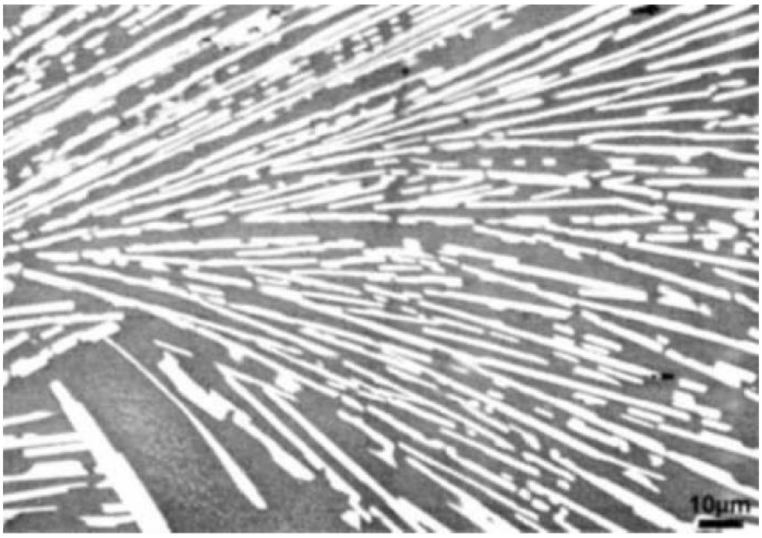
In the Figure 8 the petallike or fibrous VC particles radiate outwards from the center of the cellular colony. Petallike morphology is with a central heart and a few little ramifications with a big diameter.



Branched petallike

Figure 9 : SEM figure of an Fe-V-Ta-C alloy slowly cooled from the liquid at 5°C/min. [3]

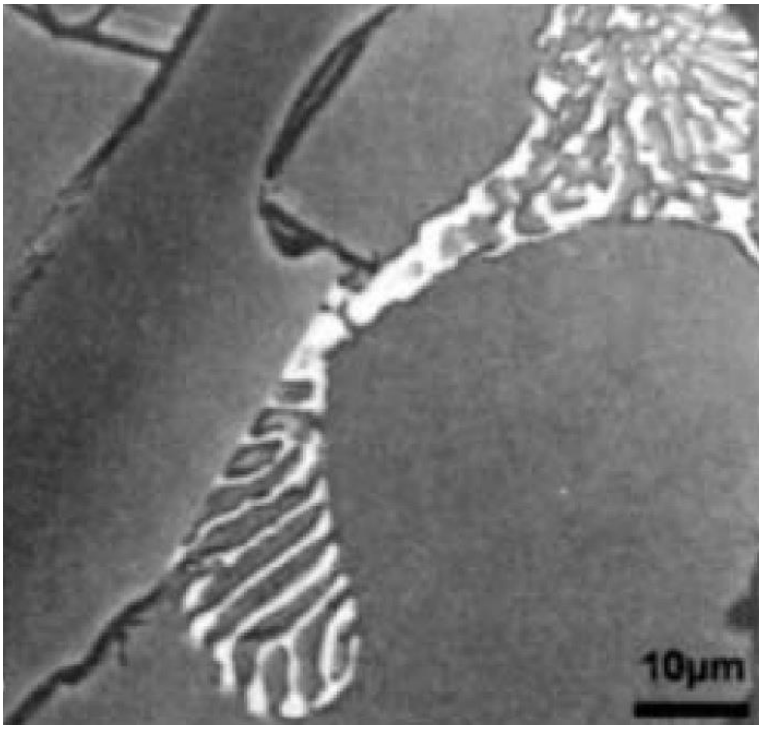
In the Figure 9 Austenite dendrites are surrounded by a (V,Ta)C eutectic. The dark carbides are rich in vanadium and the light carbides are rich in tantalum. Branched petallike is a connected structure of long branches usually situated in the inter-grain zones.



Irregular

Figure 10 : SEM figure of a Fe-C-Mo alloy; the carbides present is a eutectic Mo_2C. [3]

The irregular is characterized by radiating clusters that does not clearly outline the interface between matrix and eutectic pool.



Complex regular

Figure 11 : SEM figure of as-solidified alloys that is Fe-3.3C-16Cr-3Mo-1Mn-0.5Si alloy (back-scattered electron Figure). [3]

In the Figure 11 Mo_2C complex irregular appears white, while M_7C_3 carbide has a dual grey contrast, corresponding to two different Mo concentrations, respectively 1.3 and 5 at %. The complex regular forms a clear outline and it forms cells with macrofacets. Here the M_7C_3 carbide shows morphology defined Massive Globular.

Lamella-like

Figure 12 : SEM figure of a Fe-Mo-C system. The M_6C particles are lamellar and some have branches at 120°. In the polished section, the carbides show a fishbone morphology. [3]

The lamella-like or fishbone morphology is characterized by the presence of a central carbide platelet from which arises secondary platelets separated from each other by the matrix phase. [12]