



High Performance Materials for extreme Energy Intensive Industry Process Environments

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High Performance Materials for extreme Energy Intensive Industry Process Environments

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1. Introduction

Horizon 2020 Call: H2020-NMBP-ST-IND-2018-2020 (INDUSTRIAL SUSTAINABILITY)

Title: Advanced design, monitoring , development and validation of novel **High PERFORMANCE MATerials** and components (HIPERMAT)



1. Introduction

Motivation for this work

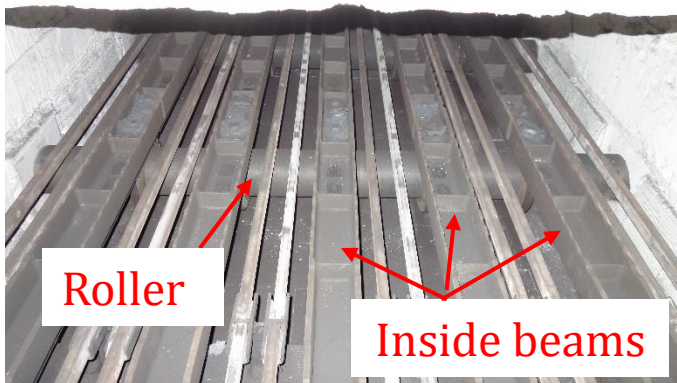
Failures observed in parts of a rolling beam furnace of the hot stamping process. In this furnace steel blanks are moved through the furnace, by combining horizontal and vertical movements of the furnace beams. The horizontal advancing mechanism is composed of metallic beams supported on rollers with rings.

The material grade used for beams and rings is the heat resistant austenitic steel AISI 310.

Rolling beam furnace (exterior)



Rolling beam furnace (interior) with beams and rollers



1. Introduction

This equipment works under:

- Fluctuating high temperature conditions at the entrance of the furnace (from 450 to 750°C).
- High loads due to the own weight of beams and the charge.
- Corrosive environments due to the combustion gases, and continuous high temperature exposure inside the furnace, in the range of 930-970°C.

When exposed to such high temperatures for long periods, the furnace parts undergo microstructure degradation resulting in deterioration of mechanical properties which can cause failure.

1. Introduction

Main failure modes are:

- Thermal fatigue of the **furnace entrance beams**
- Combined corrosion and creep of the **inside beams**
- Combined corrosion, creep and wear of **rings**

Costs, scrap and energy consumption:

These components represent 12% of the total cost of the furnace and are responsible for six maintenance stops per year.

Over the 30-year service life of a furnace 150 t of scrap are generated only due to spare parts for beams and rings and near 200 MWh are consumed in casting new steel components.

Aim of this work:

To improve the high temperature performance (creep) and extend the service life of the currently used material without increasing the manufacturing cost too much.

2. Materials and methods

Patent in progress

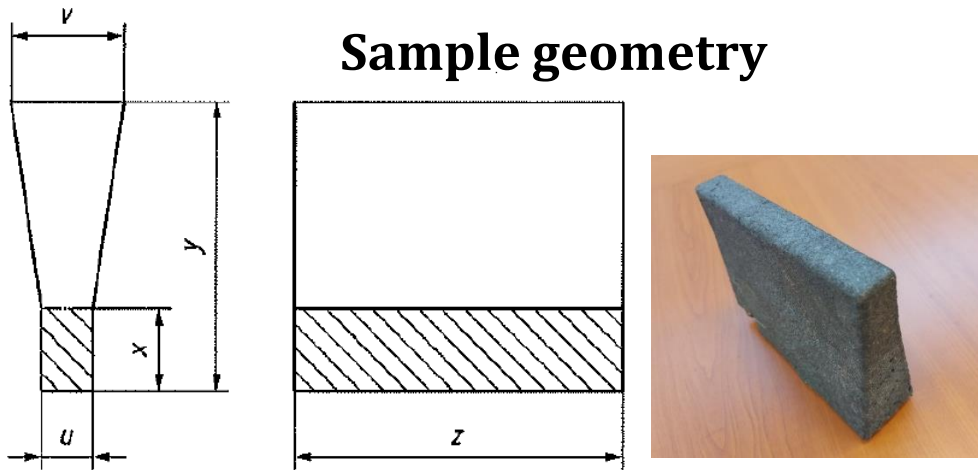
EP23382534.8

Elements (wt. %)	Ref.	Beam Inside		Beam Entrance		Ring	Grade
	AISI 310 (1.4848)	Alloy 1	Alloy 2	Alloy 3	Alloy 4	Alloy 5	1.4848
C	0.32	0.40	0.55	0.52	0.36	0.52	0.3-0.5
Si	1.21	1.63	1.71	1.77	1.66	1.69	1.0-2.5
Mn	0.95	0.94	0.93	0.98	0.98	0.92	2.00 max
Mo	-	0.62	0.61	0.60	0.61	0.57	0.5 max
Cr	24.50	24.7	24.50	19.20	18.80	24.70	24.0-27.0
Ni	17.90	20.80	21.50	20.60	25.00	21.00	19.0-22.0
Nb	-	-	0.46	0.48	-	-	
W	-	-	1.46	1.65	-	-	
Fe	55.12	50.91	48.28	54.20	52.59	50.60	Balance

2. Materials and methods

Conventional gravity casting process

Alloys were molten in an induction furnace with a capacity of 100 kg, followed by the transfer to a tea pot ladle and later direct pouring into a chemical bonded sand mold to obtain keel blocks of the geometry shown below. Samples were extracted from the dashed area. Pouring temperature was 1550 °C.



Induction furnace



Measures (mm)	u	v	x	y	z
Keel block	25	55	40	140	140

2. Materials and methods

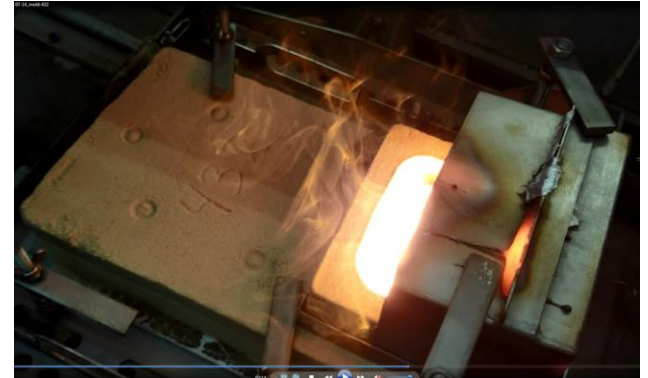
Hydrosolidification process



Lower part of the sand mold



Mold before filling



Filled mold already tilted

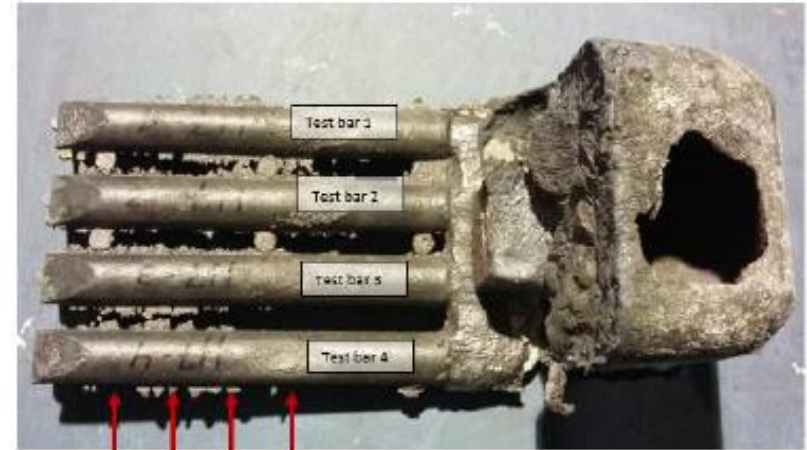
Mold basin

The metal is poured at 1550 °C into the mold basin and then a tilting takes place putting the mold in a vertical position and assuring the feeders and bar are filled up correctly. In the figure on the right side it can be observed how the metal remains filled up after tilting.

2. Materials and methods

Hydrosolidification process

The system consists of a set of water jets that are activated by a PLC (Programmable Logic Controller) dissolving the mold at the beginning far from the riser and then approaching to it. The mold has been equipped with 4 thermocouples to capture the temperature evolution over the length of the bars.



Location of thermocouples type K

Mold dissolution and metal cooling down process sequence.



Initial cooling point



Intermediate cooling point

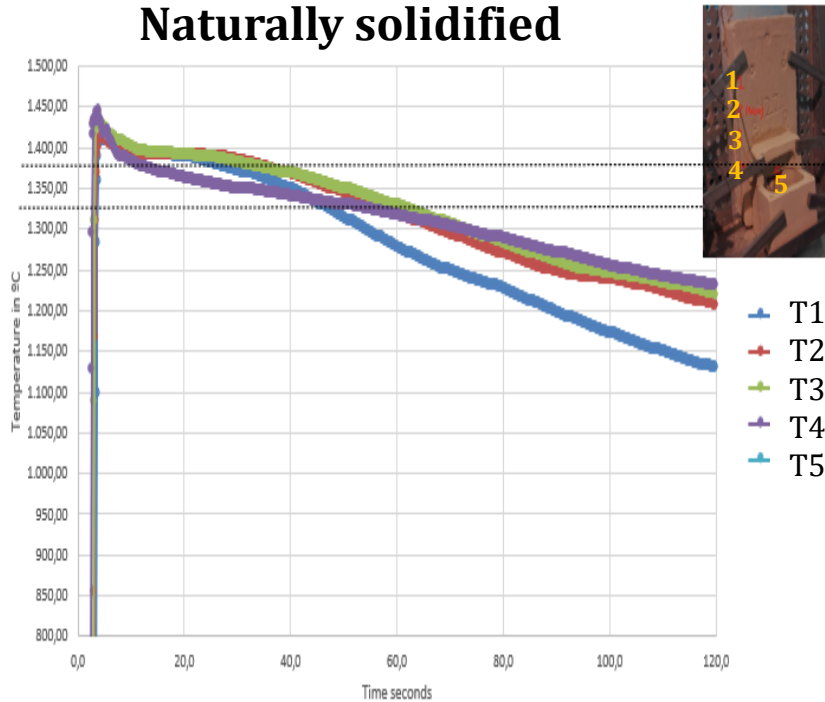


Final cooling point

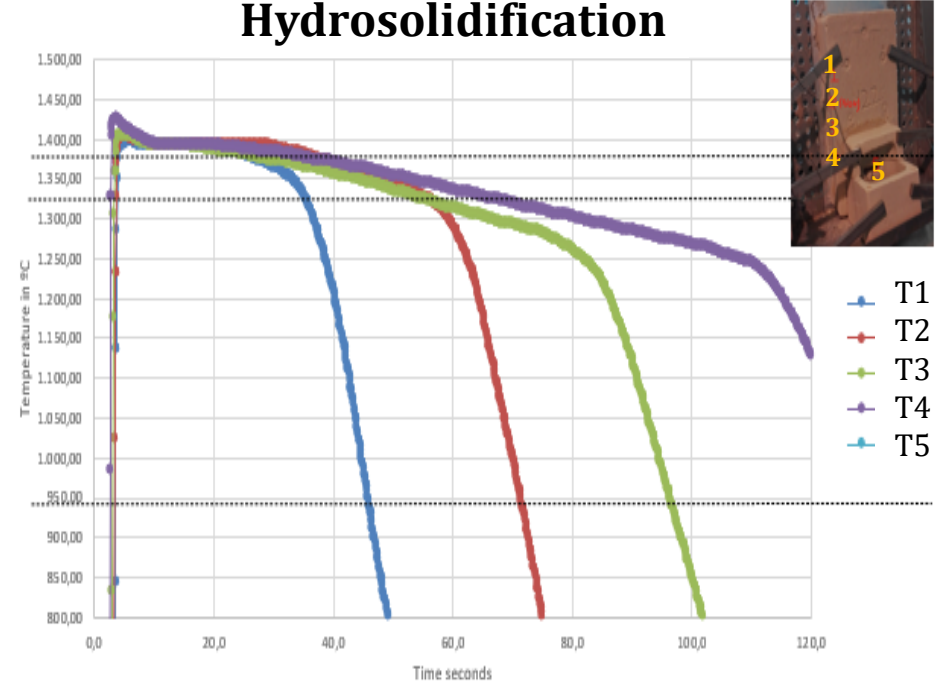
2. Materials and methods

Hydrosolidification process

Naturally solidified



Hydrosolidification



The objective is that the cooling takes place within the temperature range between liquidus and solidus (indicated in dotted lines in the graph).

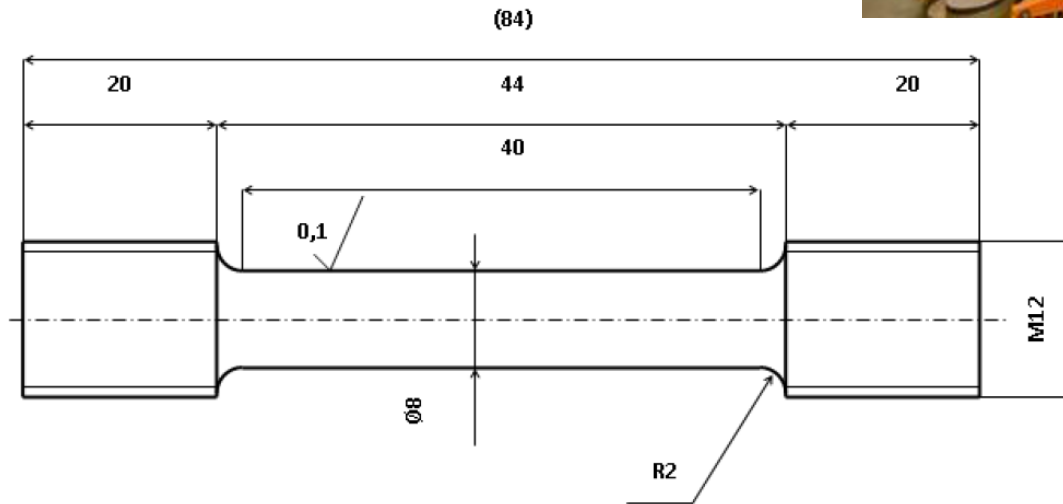
2. Materials and methods

Creep test conditions:

- a) $T = 930\text{ }^{\circ}\text{C}$, Stress = 48 MPa
- b) $T = 950\text{ }^{\circ}\text{C}$, Stress = 25 MPa



Creep test specimen



3.-Results – Alloy development

Phases formed at high temperature exposure of AISI 310

Sigma Phase (σ)

The hard and brittle σ is probably the most undesirable intermetallic phase in austenitic stainless steels. In creep resistant steels it has detrimental effect on creep properties when precipitated on grain boundaries, but not when precipitated intragranular.

The approximate composition of sigma phase in austenitic stainless steels can be written as: $(\text{Fe, Ni})_3(\text{Cr, Mo})_2$.

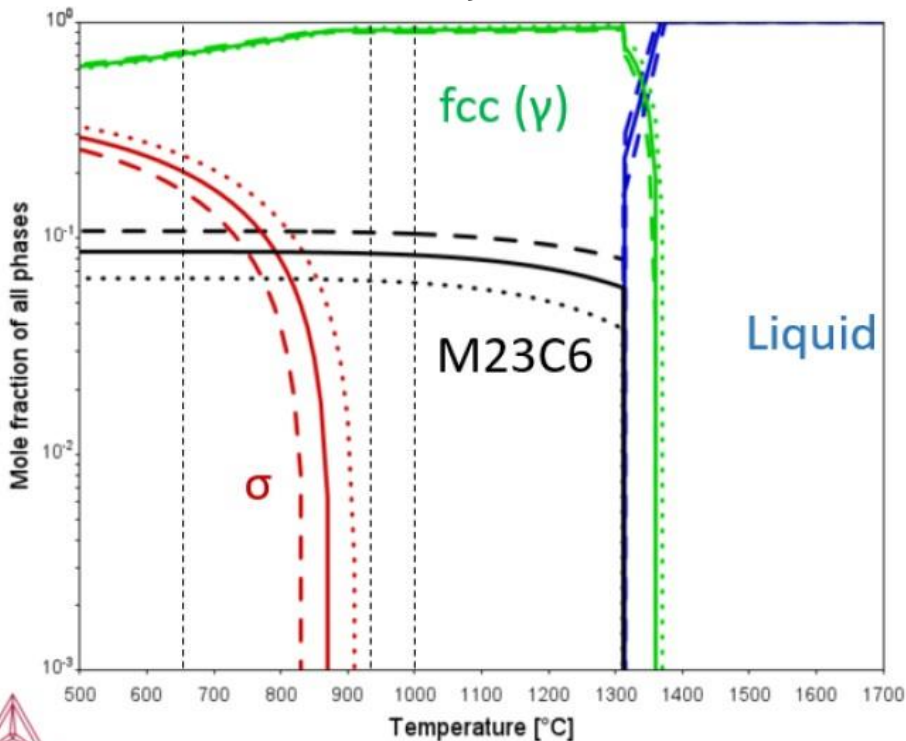
M_{23}C_6

Cr_{23}C_6 , is the most common carbide in non-stabilized carbon containing austenitic stainless steels. In general, this carbide is rich in Cr, but Fe, Ni, Mn and Mo can partially substitute Cr. High temperature exposure for during service, leads to the precipitation of fine carbides within the austenite grains. These fine and dispersed carbides enhance the creep strength of the alloy. However, prolonged exposure at high temperature will cause carbide coarsening. Once carbides exceed a certain size, their interaction with dislocations becomes less effective, and the alloy starts losing strength.

3.-Results – Alloy development

Thermodynamic calculations of AISI 310 (current alloy).

Equilibrium step diagram showing phase fractions as function of temperature (dashed lines for high carbon content and dotted lines for low carbon content).

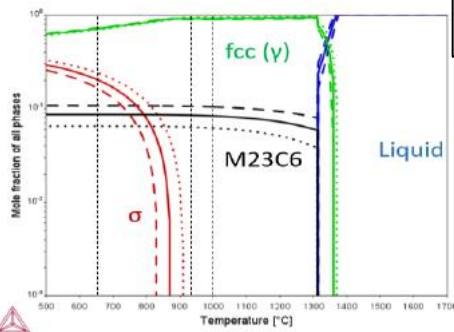


- The main phase formed are austenite, $M_{23}C_6$ carbides, and Sigma phase.
- A higher carbon content increases the amount of $M_{23}C_6$ carbides and reduces the phase fractions of σ phase as well as the σ phase solvus temperature.
- Additionally, the solvus temperature of sigma phase is reduced from about 900 to 830 °C.
- At 930 °C inside the furnace no Sigma phase is expected to form.
- But, at the furnace entrance fluctuating temperatures from 450 to 750 °C occur and Sigma phase could be formed during prolonged exposure in this temperature range.

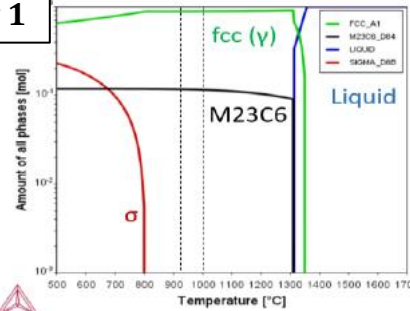


3.-Results – Alloy development

310



Alloy 1



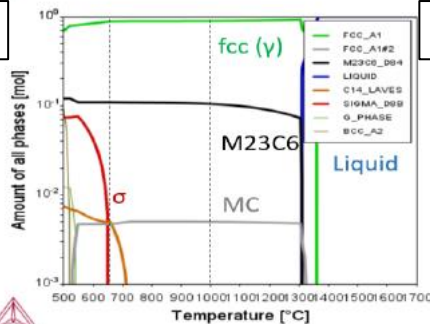
- **AISI 310 (Low C):** Sigma phase solvus temperature is 850 °C.
- **Alloy 1 (Low C, Mo addition):** Sigma phase solvus temperature is reduced from 850 °C to 800 °C.

- **Alloy 2 (high C, Mo, W, Nb addition):** Sigma phase solvus temperature is reduced to 650 °C. Additionally, MC carbides are formed at prolonged times at 930 °C.

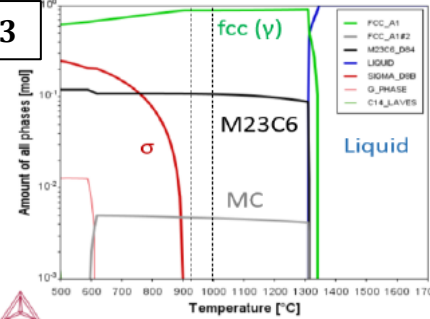
- **Alloy 3 (high C, Mo, W, Nb addition):** Sigma phase solvus temperature is 900 °C. Additionally, MC carbides are formed at prolonged times at 930 °C.

- **Alloy 4 (high C, low Cr, Mo, W, Nb addition):** Sigma phase solvus temperature is 850 °C.
- **Alloy 5 (high C, low Cr, Mo addition):** Sigma phase solvus temperature is 850 °C.

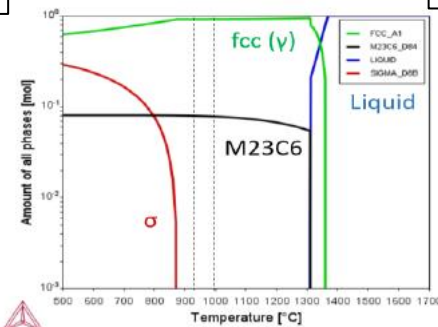
Alloy 2



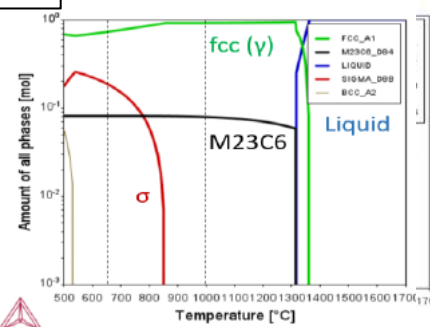
Alloy 3



Alloy 4

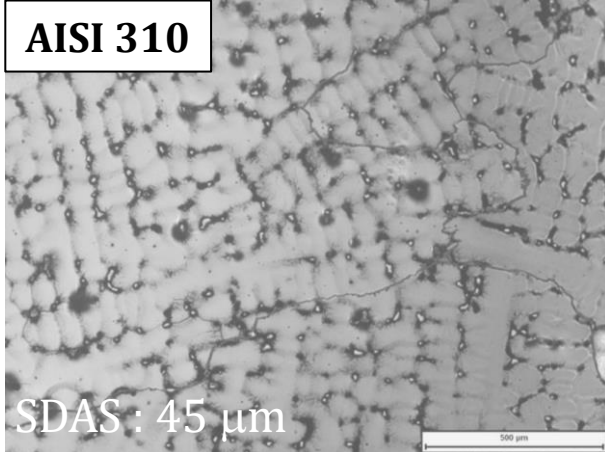


Alloy 5

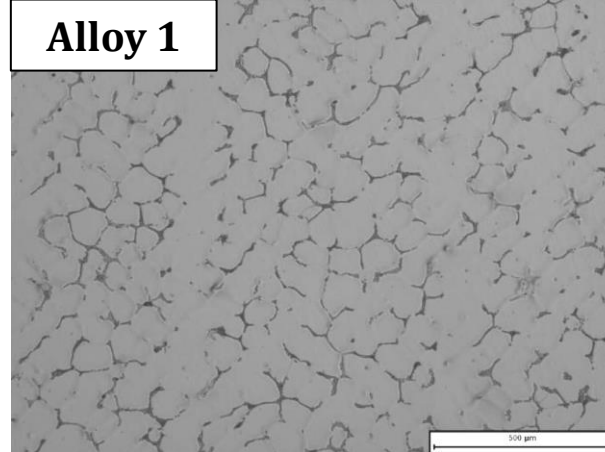


3.-Results - As-cast microstructure

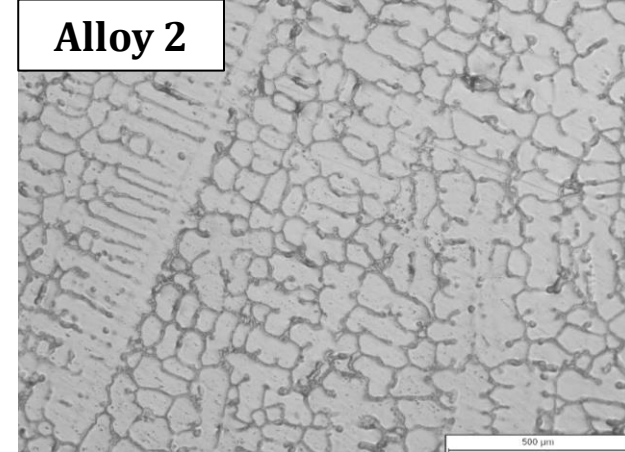
AISI 310



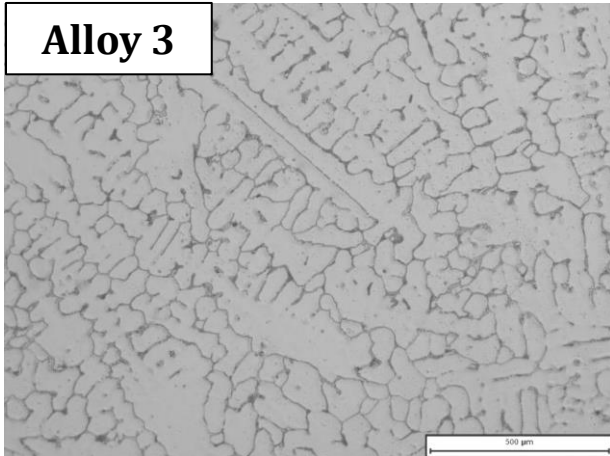
Alloy 1



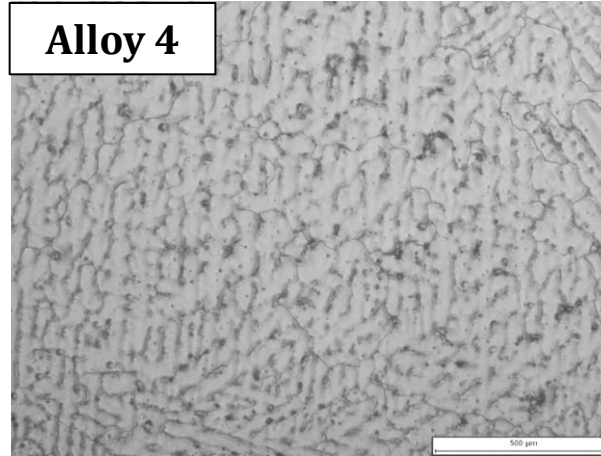
Alloy 2



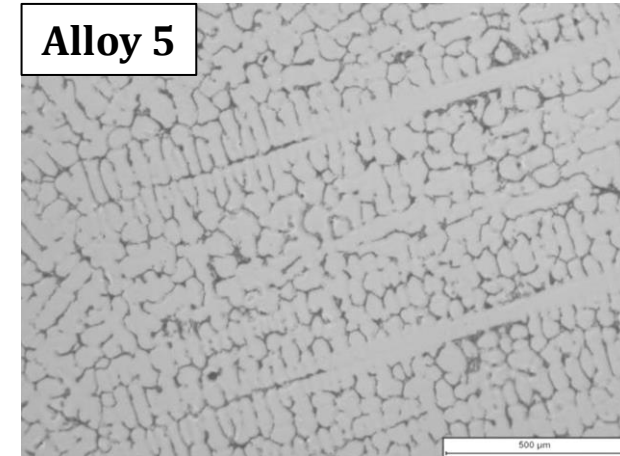
Alloy 3



Alloy 4

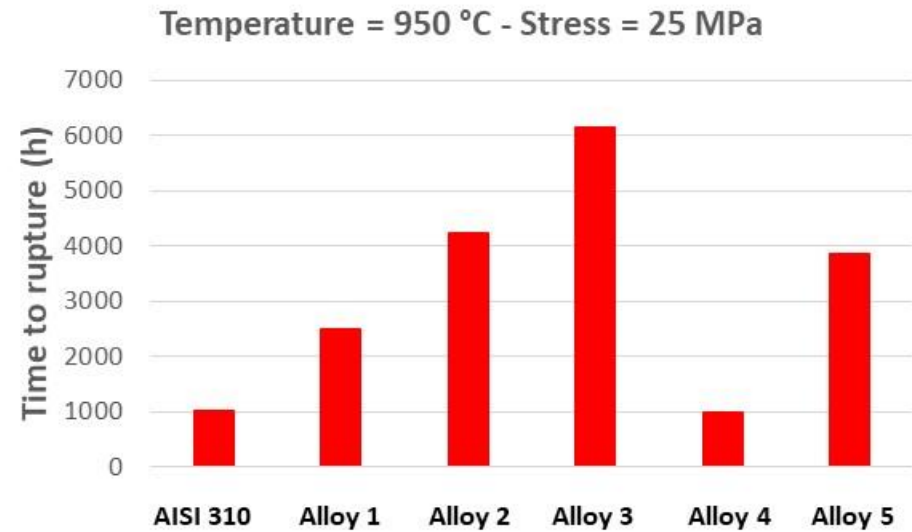
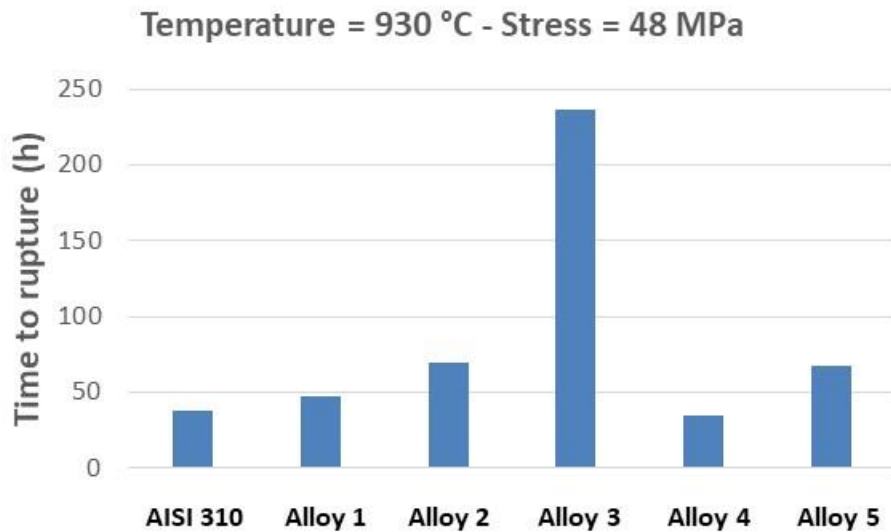


Alloy 5



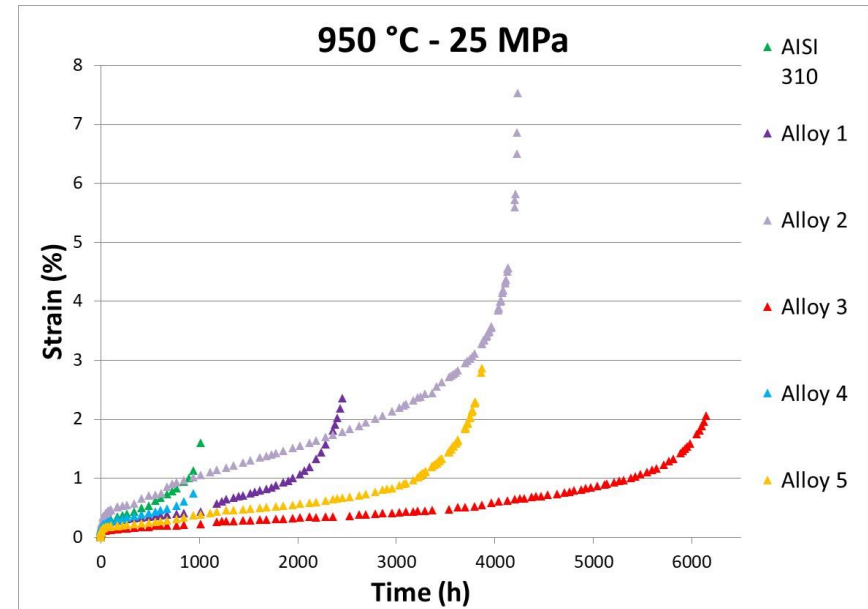
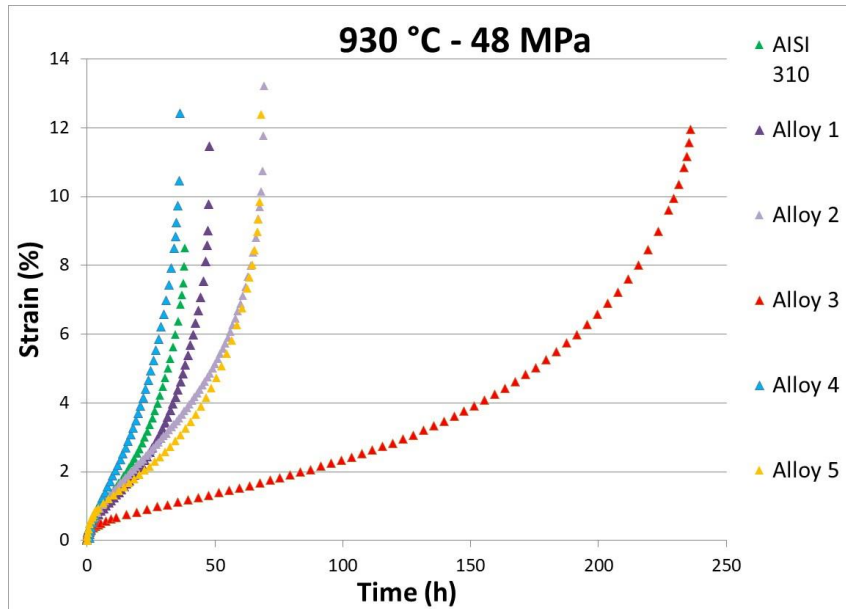
The microstructure in the as-cast state of all phases is formed by austenite dendrites and carbides located in the interdendritic spaces.

3.-Results - Creep tests of new alloys



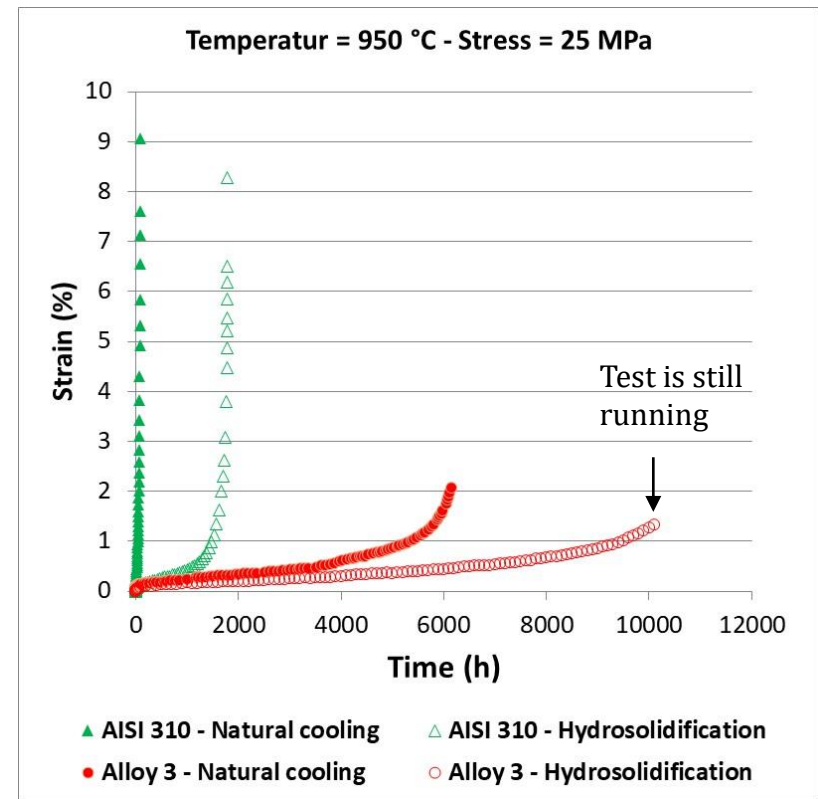
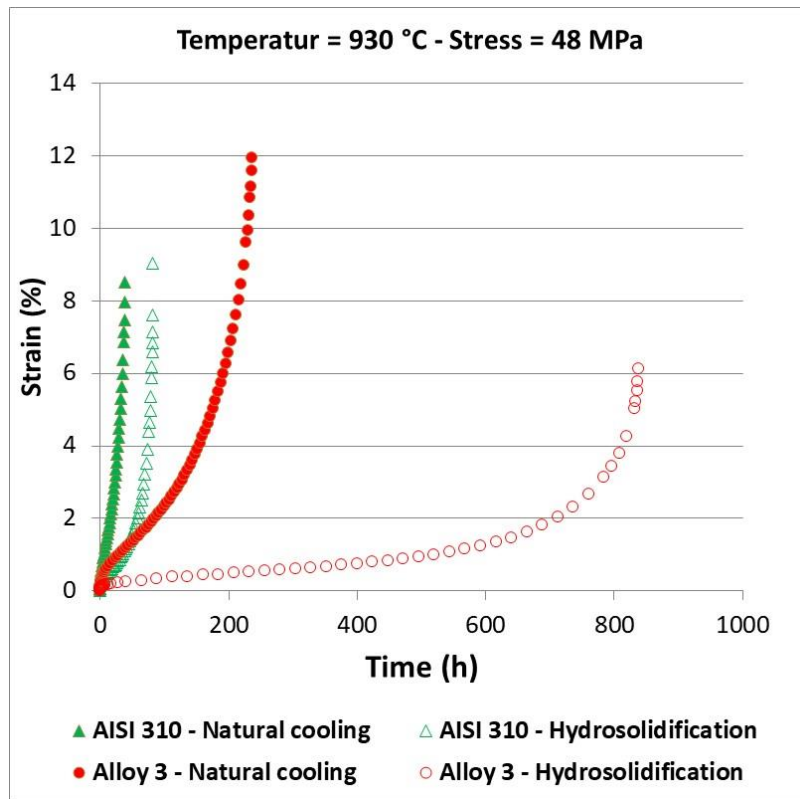
- At a temperature of 930 °C and stress of 48 MPa alloy 3 shows a considerable larger time to rupture than the other alloys.
- At 950 °C and 25 MPa the reference alloy AISI 310 and alloy 4 show the lowest time to rupture and alloy 3 the highest.

3.-Results - Creep tests of new alloys



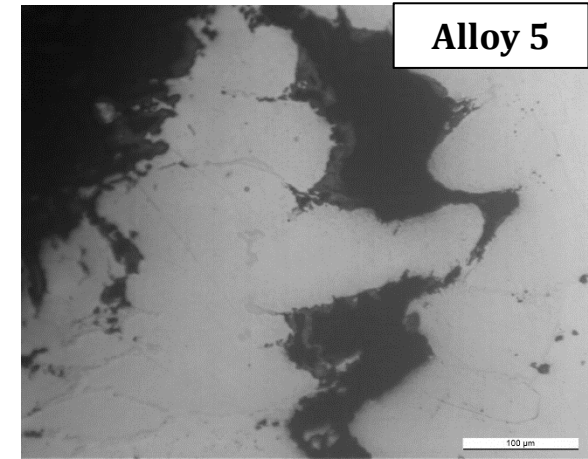
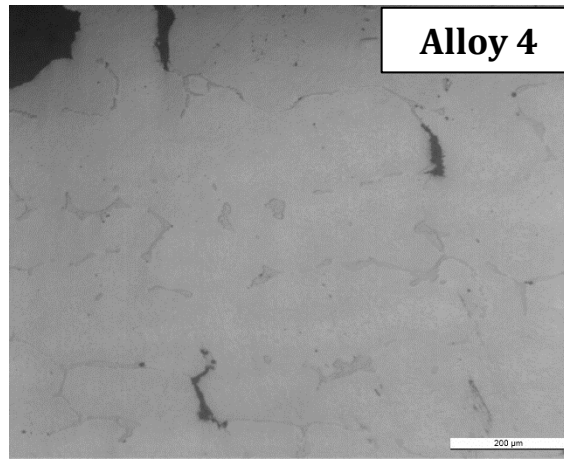
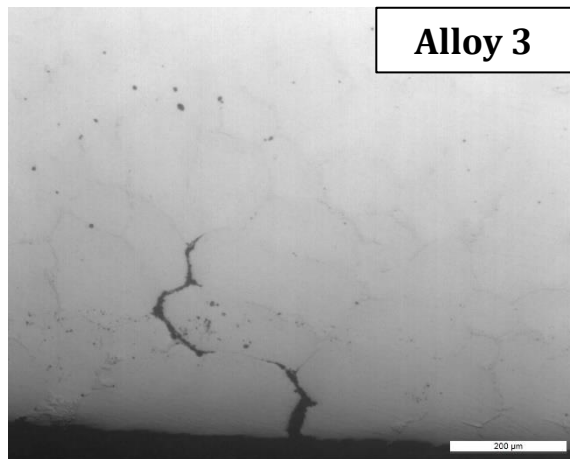
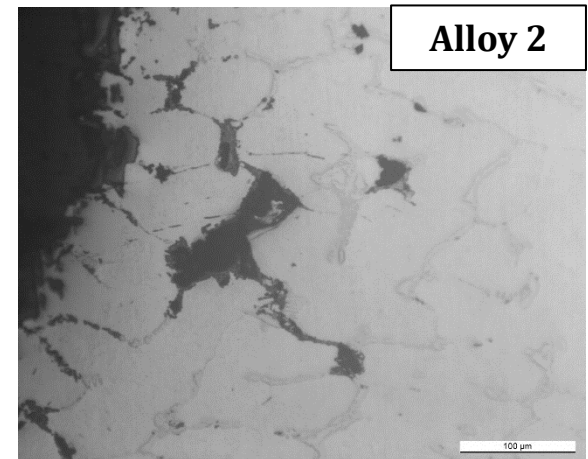
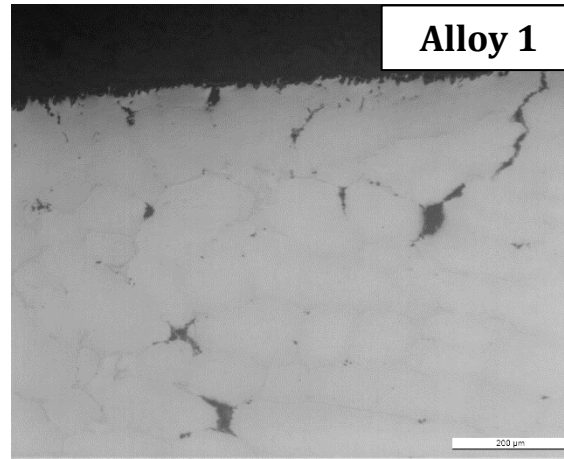
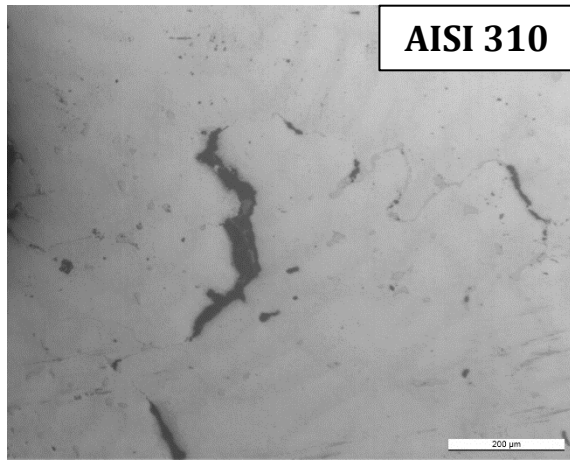
- In both conditions alloy 3 shows a considerable larger time to rupture, while alloy AISI 310 and alloy 4 have the lowest time to rupture.

3.-Results - Creep test of hydrosolidified alloys



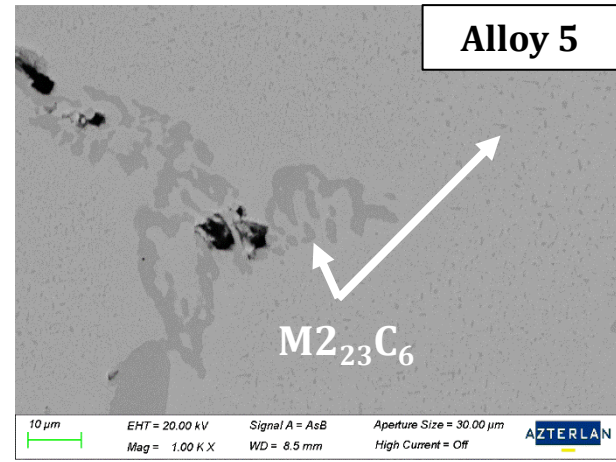
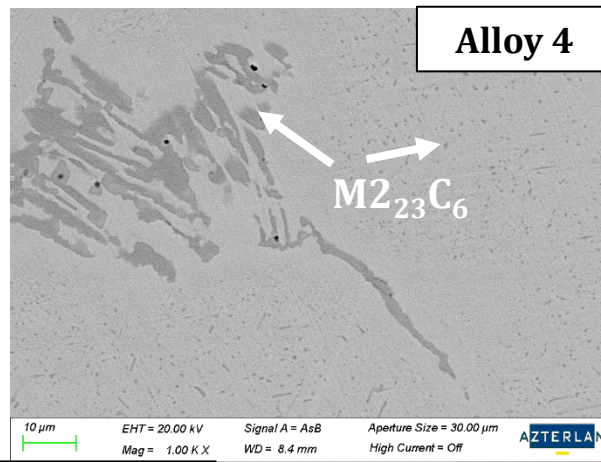
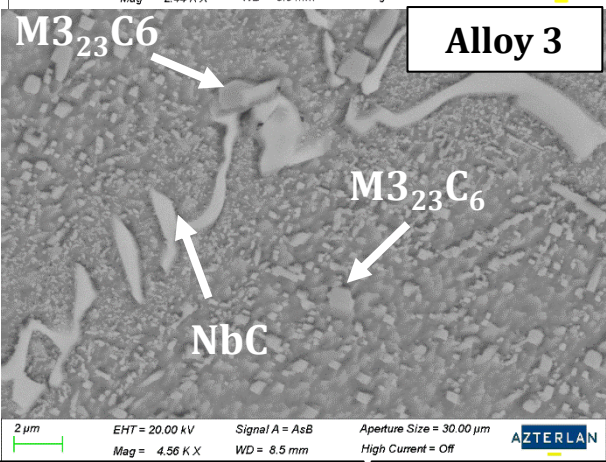
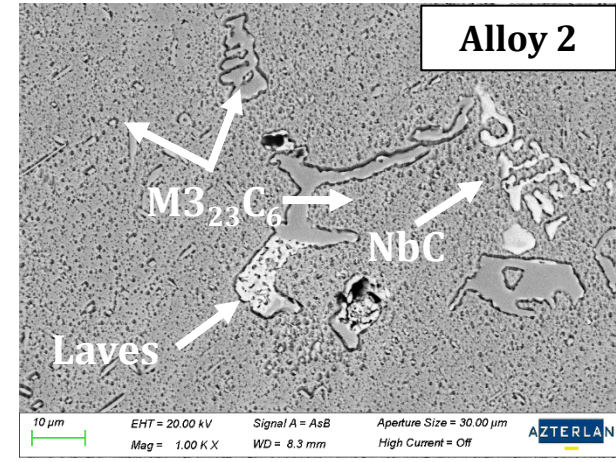
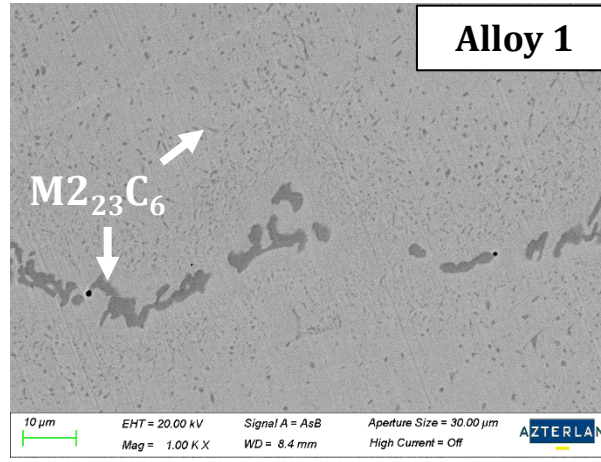
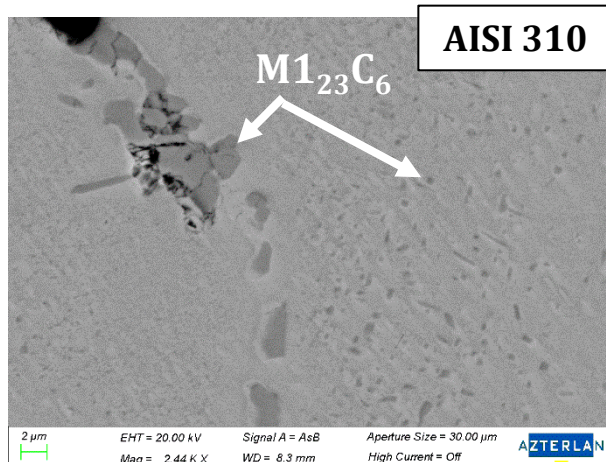
- In both creep test conditions the hydrosolidified alloys (AISI 310 and alloy 3) show significantly larger times to rupture.

3.-Results - Microstructure after creep test



Cracks initiate and propagate through the interdendritic spaces with carbides.

3.-Results - Microstructure after creep test



M1 = Cr, Fe, Ni, Mn

M2 = Cr, Fe, Ni, Mo, Mn

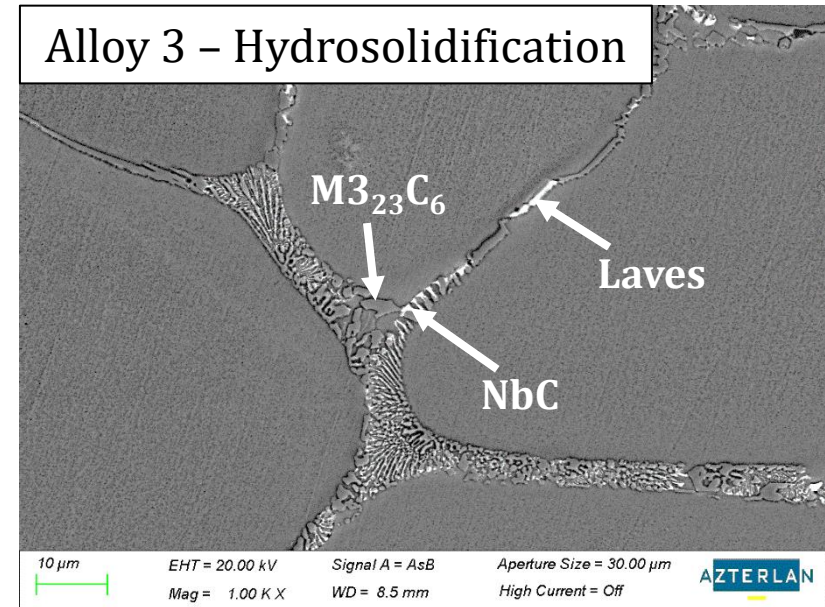
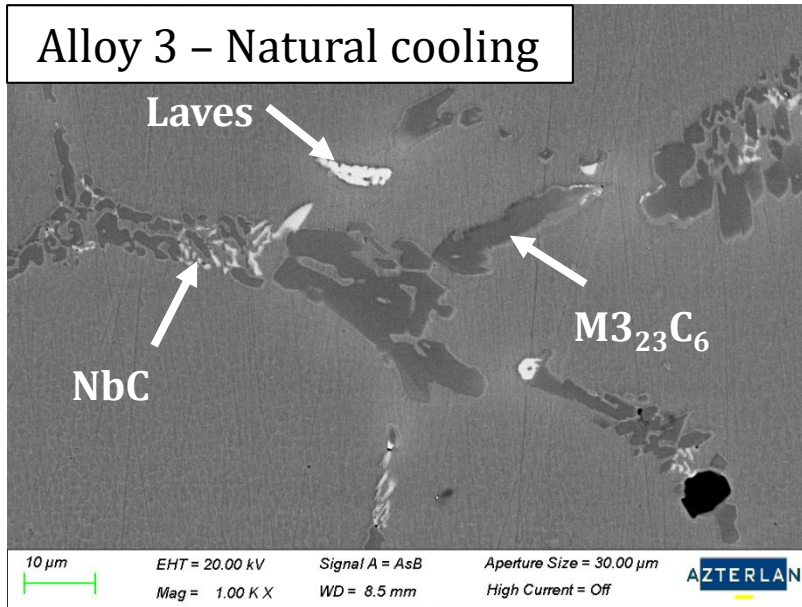
M3 = Cr, Fe, Ni, W, Mo, Mn

Laves = Cr, W, Ni, Fe, Nb, Si

- The microstructure of all samples consists of austenite and eutectic and M₂₃C₆ carbides. Alloy 2 and 3 present additionally eutectic Nb carbides and Laves phases formed during solidification.
- Furthermore, all samples show plenty of small secondary M₂₃C₆ carbides. No secondary NbC carbides have been observed in these alloys. Maybe higher magnification or TEM will be required.
- A deeper investigation of the precipitates formed during creep regarding sizes and volume fractions will be necessary to explain differences in creep behavior.

3.-Results - Microstructure as-cast

Comparison of carbides formed during natural cooling and hydrosolidification



- Eutectic carbides in the as-cast state are much finer in the hydrosolidified alloy, also the amount of carbides seems to be lower.
- The larger carbide size in the naturally solidified alloy may favour crack initiation.

4.-Conclusions

- ✓ Among the different alloys studied alloy 3 (which has small additions of Mo, W, Nb and higher C and lower Ni content with respect to the currently used alloy (AISI 310)) shows significantly better creep properties than the other alloys.
- ✓ A first microstructure analysis does not allow to justify the observed difference in creep properties of the different alloys. A deeper investigation of the precipitates formed during creep regarding sizes, volume fractions and compositions will be necessary.
- ✓ Additionally, the creep properties of alloy 3 are further enhanced when solidified rapidly by applying water spray (hydrosolidification) in the in the last stage of solidification when eutectic carbides are formed.
- ✓ These carbides are much finer, which could be favourable with respect to crack initiation.