Deliverable D1-8: Public Database

Ghent University
Delft University of Technology

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Dissemination level
Version V[1.0]

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Introduction

Deliverable D1-8 of Work Package 1 Functional grading provides in the form of a database an overview of all the test results obtained during testing of the coupons.

This includes the intended materials for the printing of the coupons. It should be mentioned that not all materials initially indicated are actually applied. The proposed materials and the characterisation techniques envisaged are also included in this page.

In the subsequent sheets the test results of each of the demonstrators are mentioned. Details of the wires applied and test results can be found in the deliverable 1.1, 1.3 and 1.5.

WP 1

No.	Demonstrator	End-user	Application	dimensions test coupon (lxwxh) in mm	GRADED SPECIMENS - PROPOSAL																			
					625/S355 or eventually S460	718 [heat treatment]/S355	316L/S355	2205/S355	2207/S355	420/S355	410/S355	alloy 36	graded invar	55NiFe/spheroid graphite iron	55NiFe/ HSS (P20)	Iron-based hard facing/ spheroid graphite iron	hard facing /HSS	NAB/cast iron	NAB/HSS	Hard-faced, Nb/ X37CrMoV5-1.	Hard-faced Mo/ X37CrMoV5-1.	Hard-faced, V/ X37CrMoV5-1.	Hard-faced, W/ X37CrMoV5-1.	Hard-faced, Co/ X37CrMoV5-1.
A-1	Propeller*	MAN ES	Maritime	wall 200x60x300, surface graded 200x100x20	Yes #1	Yes	Yes #2	Yes #3	Yes															
A-2	Mobile ring hydroelectric plant	EDF	Energy	wall monomaterial: 200x100x80/30, bimaterial:			Yes	Yes	Yes															
B-1	Mould for bathtub showface	Villeroy&Boch	Home ware	surface sample 200x100x20, 200x8x150 (S355); Graded wall						Yes	Yes													
B-2	Mould for TP	GKN	Aerospace	wall 150x25x200								Yes	Yes											
B-3	Injection mould for plastic parts	Arrk Shapers	Automotive	multimaterial 200/100x100x50										Yes	Yes									
B-4	Forming die for steel parts	Gorenje	Automotive	200x100x20												Yes	Yes							
B-5	Forming die for stainless steel parts	Gorenje	White goods	200x100x20														Yes	Yes					
B-6	Hot forging die (repair)	Kuźnia Jawor	Heavy lifting	200x100x20																Yes	Yes	Yes	Yes	Yes

No.	Specimens produced at:		Metallography													
	RAMLAB, by date:	Naval Group, by date:	Optical	SEM-EBSD	TEM *1	chemical analysis *2	Tensile *5	Tensile at elevated	Impact (Charpy)	Microhardness	Corrosion (OCP)	Fatigue	Surface roughness	Dilatometer *3	Abrasive wear	Scratch
			TU Delft	UGent	UGent	TU Delft	TU Delft	PWR	TU Delft	PWR/TUD	TU Delft	UGent	PWR??	TU Delft	PWR	PWR
A-1	M9 dec20		Yes	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes				
A-2		M9 dec 20	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes				Yes	
B-1	M4 july 20		Yes	Yes	Yes	Yes				Yes	Yes		Yes			
B-2	M8 nov 20		Yes	Yes		Yes				Yes				Yes		
B-3		M10 jan 21	Yes	Yes	Yes	Yes			Yes	Yes	Yes				Yes	Yes
B-4	M12 March 21		Yes	Yes	Yes	Yes			Yes	Yes					Yes	Yes
B-5	M7 March 21		Yes	Yes	Yes	Yes				Yes					Yes	Yes
B-6	5-mei-22		Yes	Yes	Yes	Yes		Yes + Troom		Yes					Yes	Yes

*X-Ray tomography in case required
*1 TEM in case required
*2 EDS/EPMA
*3 CTE, multi-axis expansion
*4 optical (keyence/confocal)
*5 TUD callibrated equipment, not ISO certified

A1 Propeller MAN ES, RAMLAB

monomaterial AM35

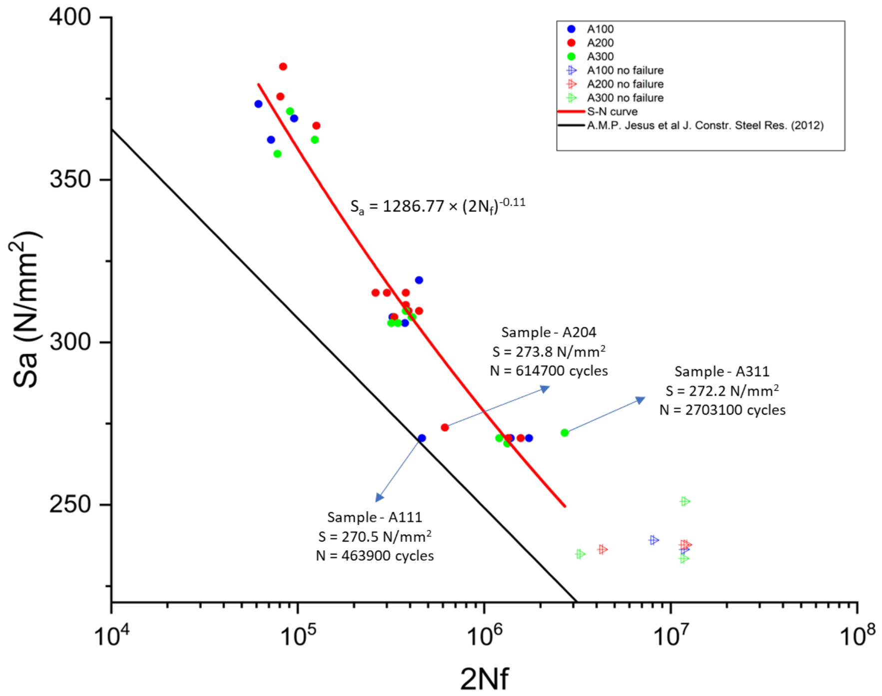
tensile testing

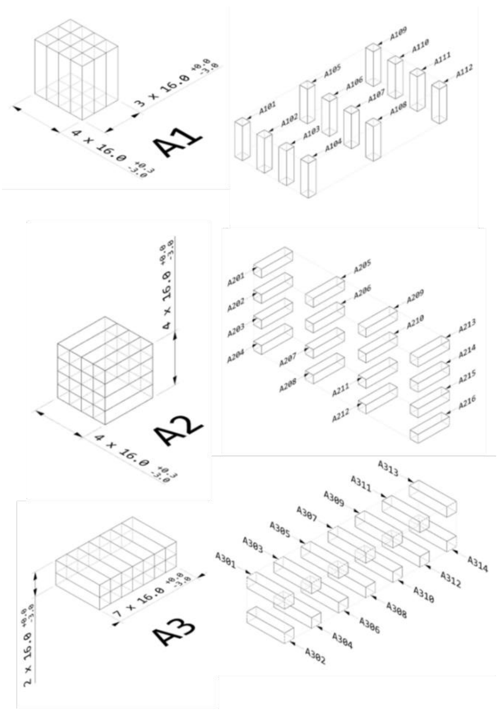
AM35

Legend	No.	Specimen ID	Notes	Emod GPa	F at 0.2% plastic strain MPa	Upper yield point MPa	Fmax MPa
	3	A506		230	408	436	503
	6	A501		236	407	430	515
	7	A502		193	404	417	503
	8	A503		199	431	451	527
	10	A504		231	398	422	501
	16	A505		209	432	463	531
	17	A507		190	403	428	508
	18	A508		206	364	391	460
	19	A401		197	392	409	498
	20	A402		210	429	458	523
	21	A403		201	391	413	508
	22	A404		201	412	438	510
	23	A405		201	394	415	506
	25	A406		201	394	406	505
	26	A407		196	393	405	496
	27	A408		215	413	433	507

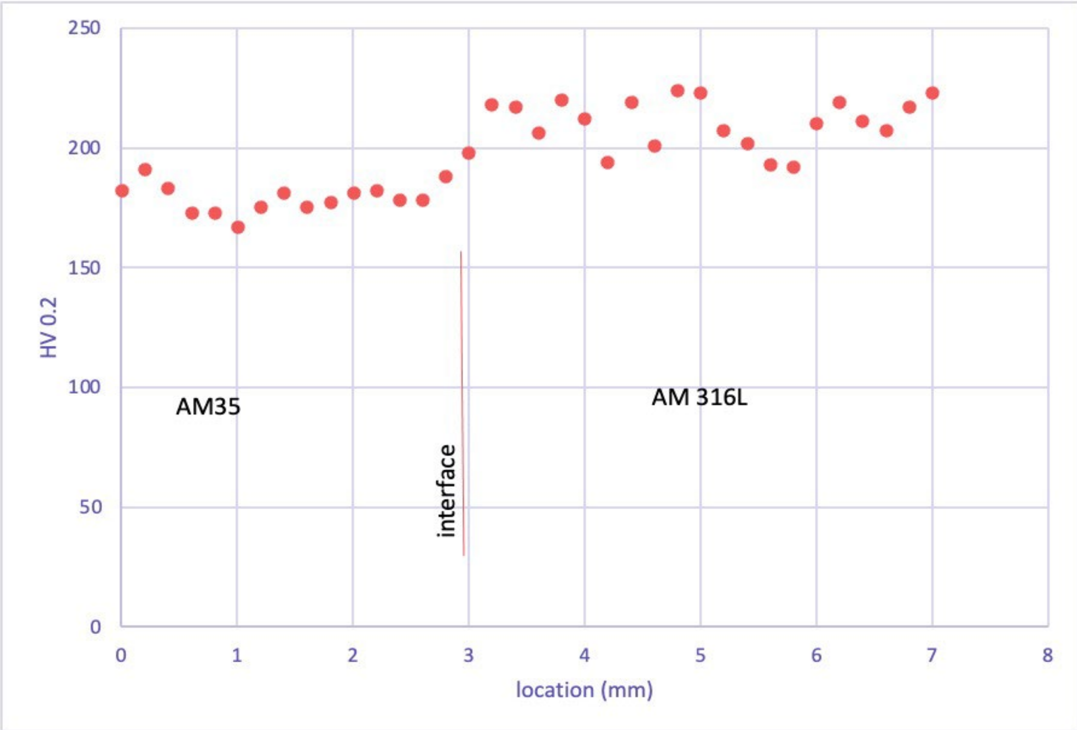
Legend	No.	dL(plast.) at Fmax mm	dL at Fmax mm	FBreak MPa	dL at break mm	d0 mm	S0 mm²	Details about break
	3	4,9	4,9	266	8,9	6,01	28,37	ok
	6	5,0	5,1	289	9,0	6,01	28,37	ok
	7	5,3	5,4	278	10,5	6,02	28,46	ok
	8	4,3	4,4	296	9,1	6,02	28,46	ok
	10	5,1	5,1	287	9,1	6,02	28,46	ok
	16	4,2	4,3	300	8,1	6,01	28,37	ok
	17	5,2	5,3	278	9,7	6,03	28,56	ok
	18	3,7	3,8	258	6,6	6,02	28,46	ok
	19	4,1	4,2	290	7,6	6,02	28,46	ok
	20	4,0	4,0	285	7,3	6,03	28,56	ok
	21	4,0	4,1	285	7,5	6,02	28,46	ok
	22	4,8	4,8	280	9,9	6,03	28,56	ok
	23	4,0	4,0	277	7,5	6,01	28,37	ok
	25	4,1	4,1	261	8,2	5,99	28,18	ok
	26	4,0	4,1	302	7,3	6,01	28,37	ok
	27	5,1	5,2	282	10,3	6,04	28,65	ok

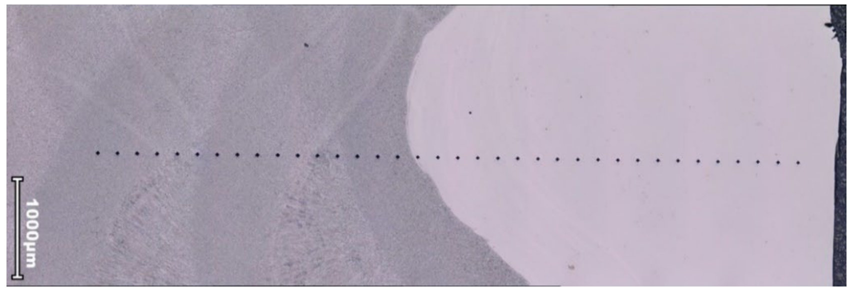
fatigue testing





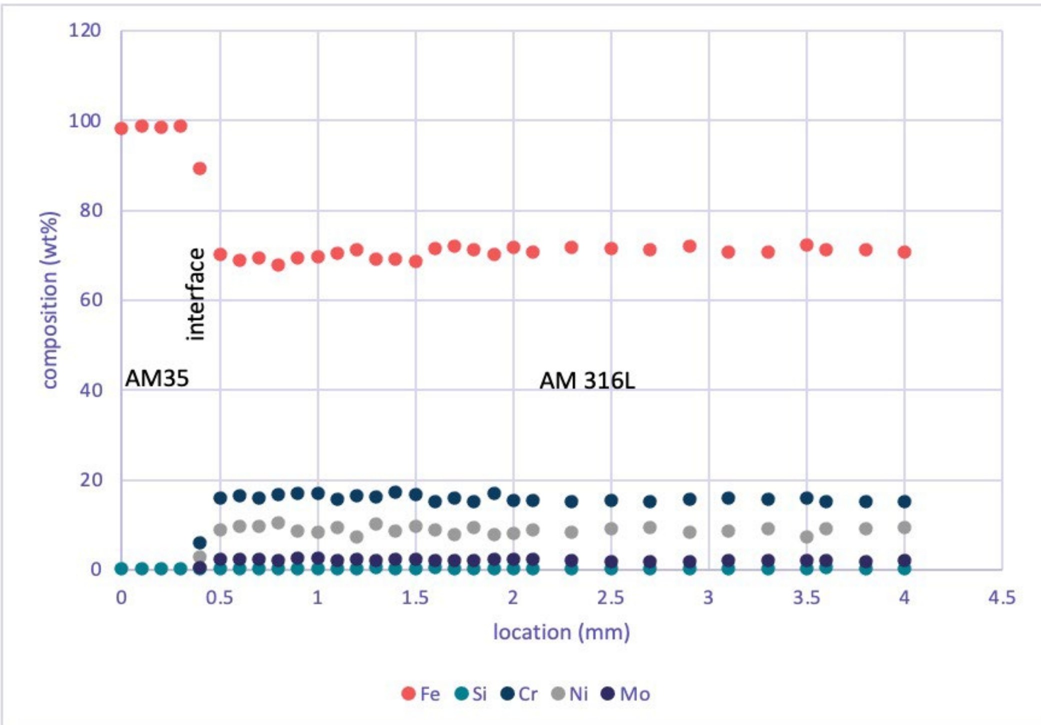
Bi material
bottom AM35
top AM316L





interface AM35 left AM316L right

micrograph AM35 bottom AM316L top



chemical composition across interface AM35-AM316L

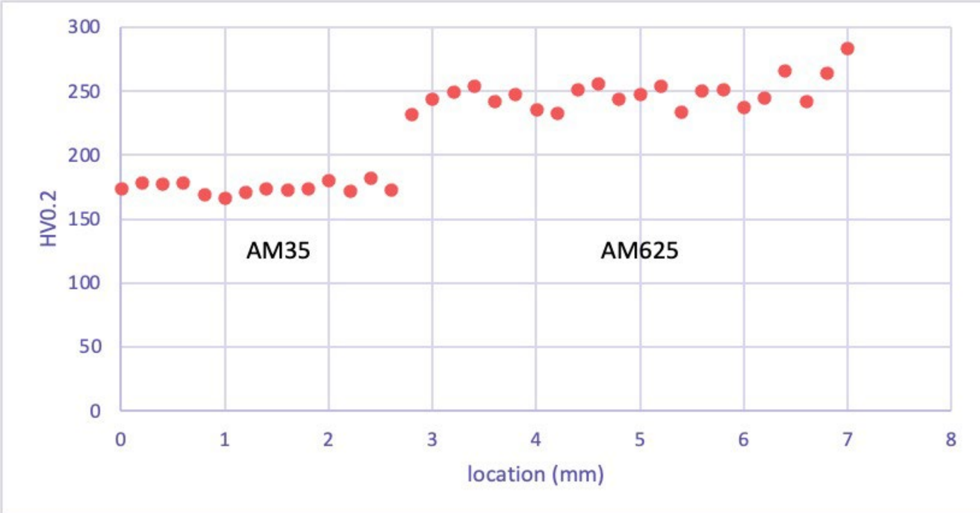
Table 2.2: corrosion data on 316L deposit on AM35, 3.6 mm from the interface.

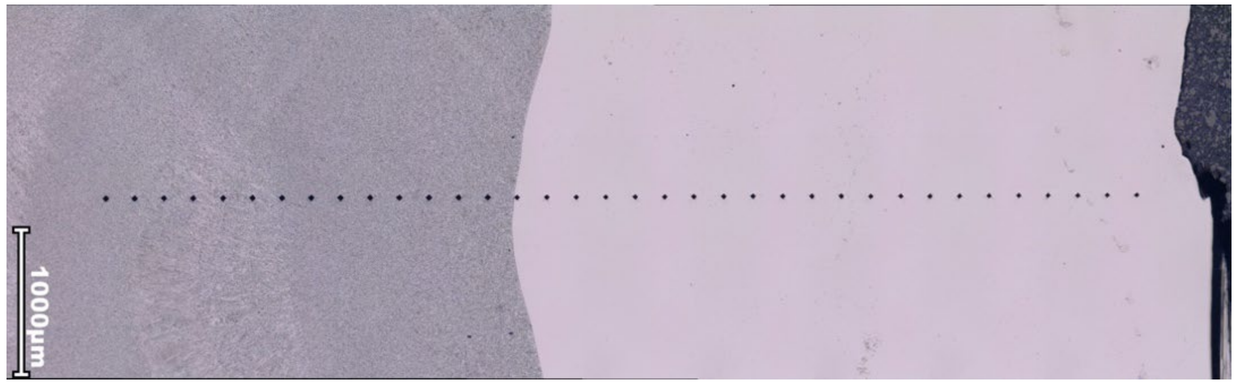
	E_{corr} (mV)	I_{corr} (µA)	β_a (mV)	β_b (mV)
A1 001	-13,54	0,011	177,9	72,7

E values obtained vs. saturated Ag/AgCl electrode ($E_{SCE} = E_{std\ Ag/AgCl}$ - 44 mV)

Exposed area is 0.785 cm^2. $i_{corr} = I_{corr}/0.785\ \mu A/cm^2$

Bi material
bottom AM35
top alloy 625





Microhardness across the interface AM35-AM625

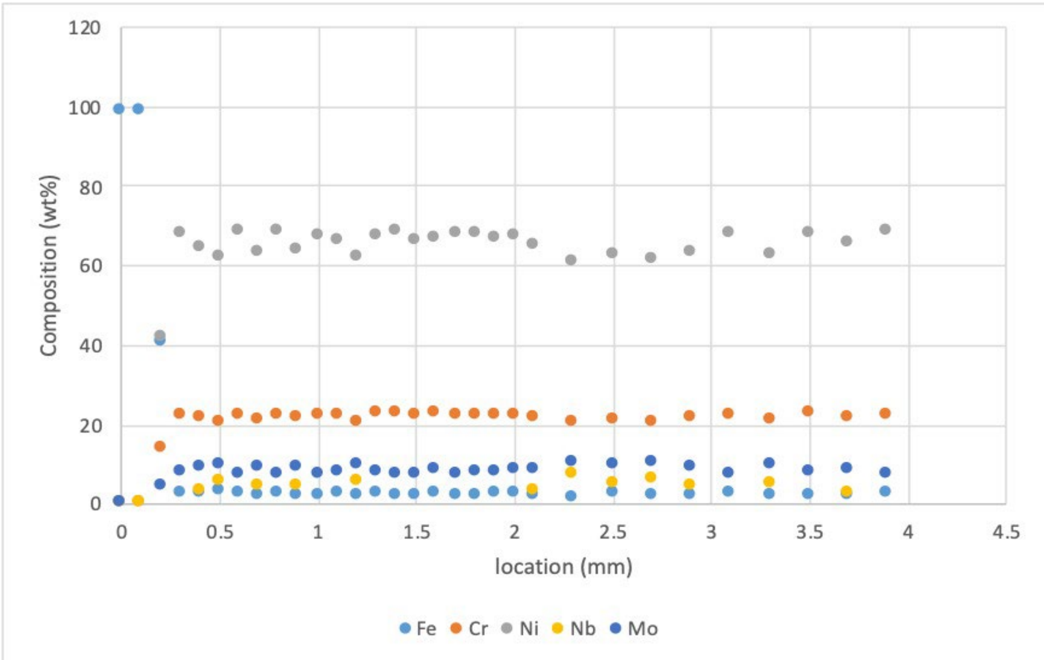
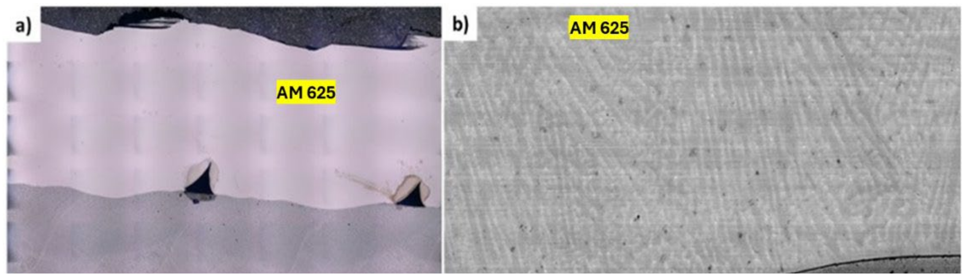
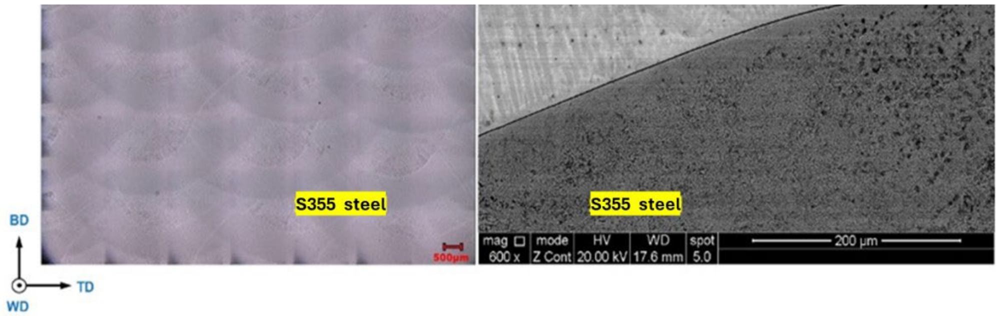
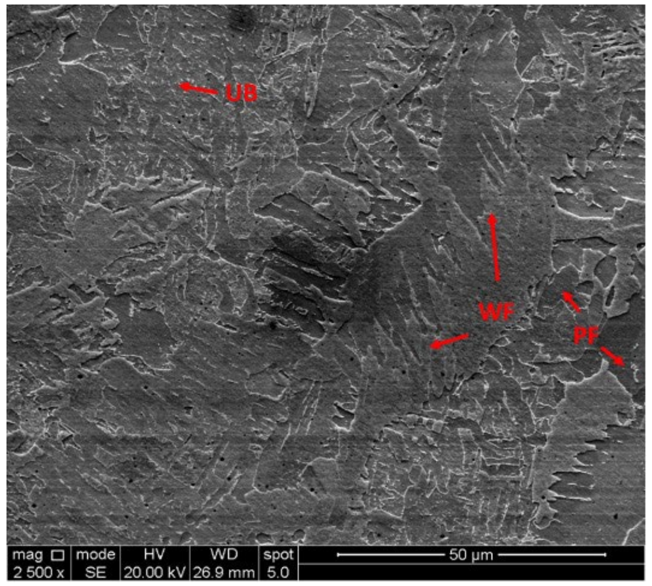


Figure 2.6: Composition across the interface AM35 - AM625

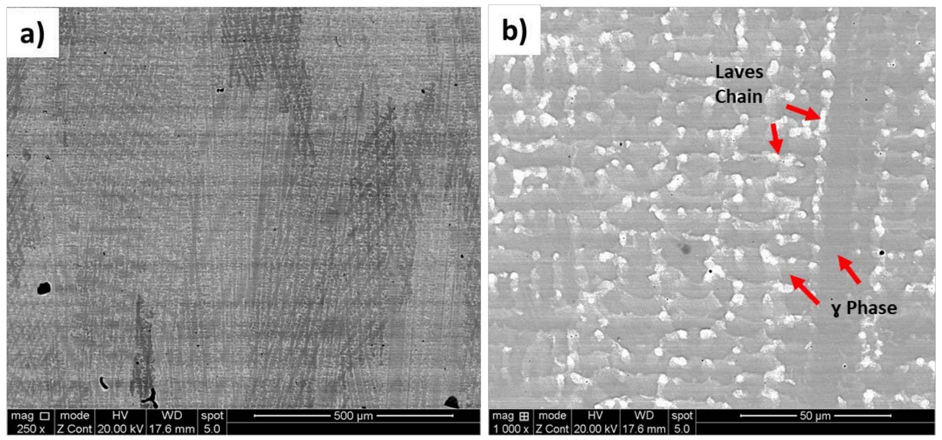




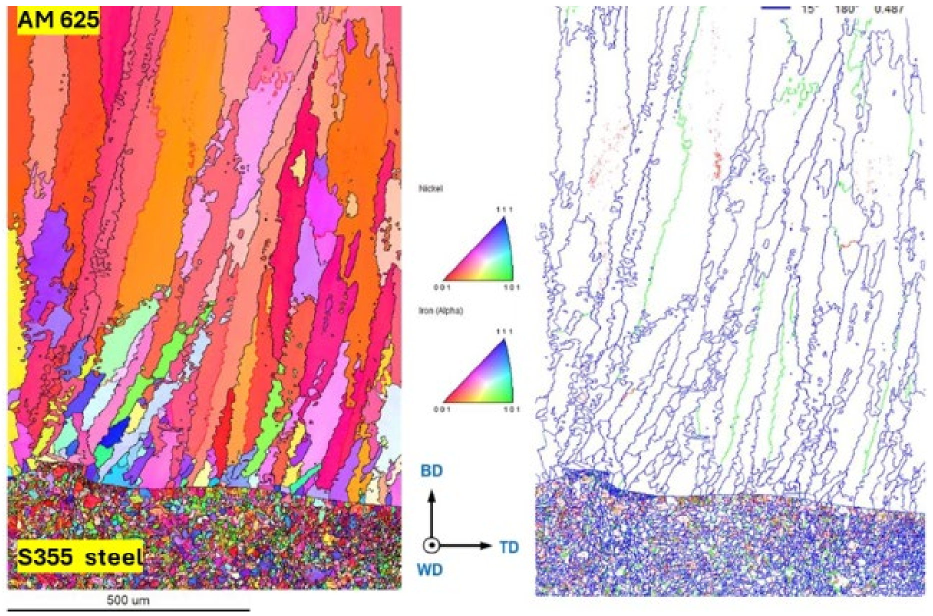
The interface region. The bottom part is AM355, and top region is AM625 superalloy (a): optical microscopy image, (b): SEM-BSE image



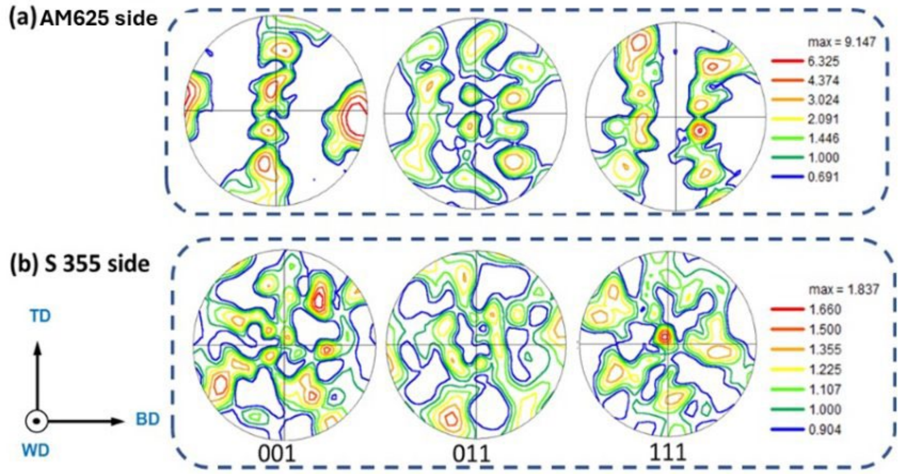
The microstructure of S355 steel, (UB: Upper bainite, PF: Polygonal ferrite, and WF: Widmanstatten ferrite)



The microstructure of deposited AM625 superalloy



EBSD results for bi-material of AM355 steel -AM625 superalloy; a): Building direction-IPF map of Bi-metal AM355 steel -AM625 superalloy



The pole figures (PFs) of different parts of the bi-material of AM355 steel -AM625 superallo

Table 2.3: corrosion data on alloy 625 deposit on AM35, 4.1 mm from the interface.

	E_{corr} (mV)	I_{corr} (μA)	β_a (mV)	β_b (mV)
A1 001	130,096	0,02	199	215

E values obtained vs. saturated Ag/AgCl electrode ($E_{SCE} = E_{std\ Ag/AgCl}$ - 44 mV)

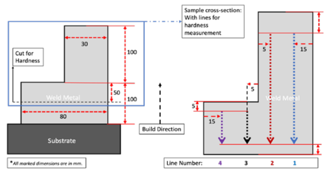
Exposed area is 0.785 cm^2. $i_{corr} = I_{corr}/0.785$ μA/cm^2

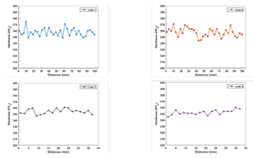
A2 Mobile ring EDF, NAVAL Group

Monomaterial block

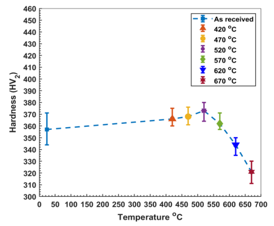
AM410

hardness



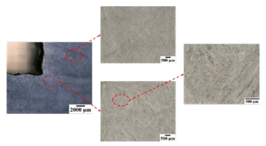


Hardness along lines indicated in figure left



Hardness of printed AM410 for several heat treatment temperatures (soak time 1hr)

macro/microstructure



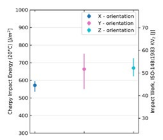
Microstructure at corner of the cross section of the mono-block at the transition from the thick bottom part towards the more slender top part, indicating a martensitic microstructure

mechanical testing

	E_mod	yield_S	tensile_S	elong	RA	Impact_W	Impact_J
n	4	4	4	4	4	3.000000	3.00000
min	199.526	846.331	1101.06	14.3939	55.5556	595.255000	47.62000
max	177.79	766.867	1066.13	2.72818	2.98738	535.277000	41.31300
avg	187.476	804.095	1083	8.50948	38.6655	571.678667	44.99300
std	7.7749	37.3957	16.8864	5.78176	20.825	26.111390	2.68032

	E_mod	yield_S	tensile_S	elong	RA	Impact_W	Impact_J
n	6	6	6	6	6	3.000000	3.000000
min	188.307	955.544	1109.77	15.7221	57.1649	750.548000	59.462000
max	170.536	878.221	1090.28	7.45475	14.3914	550.611000	42.970000
avg	181.007	914.352	1099.3	13.3788	48.0747	663.725333	52.234333
std	6.41887	29.9992	5.84315	2.79135	15.1452	83.714355	6.885130

	E_mod	yield_S	tensile_S	elong	RA	Impact_W	Impact_J
n	5	5	5	5	5	3.000000	3.000000
min	178.43	932.818	1091.56	13.7483	59.9101	726.801000	58.067000
max	172.786	921.914	1061.9	10.8583	48.2273	622.831000	48.816000
avg	175.478	927.881	1078.54	12.8404	54.1549	670.120667	53.049000
std	2.42628	4.56121	9.87069	1.03824	4.68812	42.961833	3.817278



Charpy Impact test results in three directions for AM410 at room temperature

: Tensile test results in three directions for AM410 and Charpy Impact test results in three directions for AM410 including test temperature -20 °C

As received, tested at T room and Charpy also at -20C

	Yield (MPa)	UTS MPA)	Elong (%)	Charpy (J)	Charpy -20C (J)	HV
X- (welding) direction	804± 37	1083 ±17	8.5	45 ± 2.7	32.6 ± 0.9	358
Y- (transverse) direction	914 ± 30	1099 ± 6	13.4	52.2 ± 6.8	40.8 ± 2.3	
Z- (building) direction	927 ± 5	1079 ± 10	12.8	53 ± 3.8	49.0 ± 2.3	

Mechanical test results in three directions for AM410 after a heat treatment of 580 °C for 2hrs.

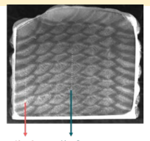
Heat Treated 2hr 580 °C

	Yield (MPa)	UTS (MPA)	Elong (%)	Charpy (J) -20C	HV
X- (welding) direction	949 ± 39	1040 ± 27	17.3	22.8 ± 10.6	350
Y- (transverse) direction	966 ± 51	1040 ± 24	17.3 (void)	40.8 ± 7.6	
Z- (building) direction	955 ± 21	1040 ± 16	15.7	33.1 ± 15.7	

Table 3.3b: Charpy impact tests results in three directions for AM410 after a heat treatment of 620 °C for 2 and 4 hrs., -20 °C

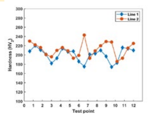
condition	*n*	*ave energy (J)*	*st dev energy (J)*
620 °C, 2hr, x-direction	*4*	*48,1*	*5,1*
620 °C, 2hr, y-direction	*3*	*78,9*	*5,8*
620 °C, 2hr, z-direction	*4*	*84,2*	*4*
620 °C, 4hr, x-direction	*4*	*56*	*3*
620 °C, 4hr, y-direction	*1*	*44,9*	*-*
620 °C, 4hr, z-direction	*4*	*73*	*5,6*

AM46



Line 1 Line 2

macrostructure AM46 block



Hardness profile AM46

Line 1 - Towards the edge
Average: 201
Max:233
Min:174

Line 2 - Middle of the section
- Average: 212
- Max:243
- Min:186

Tensile test results in three directions of mono-material block N-1200, as received condition tested at room temperature.

X / Longitudinal dir. (along bead)

	E_mod	yield_S	tensile_S	elong	RA
n	5	5	5	5	5
min	205.474	606.353	665.903	32.1469	76.636
max	166.582	543.557	613.703	27.1713	63.4794
avg	183.656	573.135	641.015	29.5573	69.279
std	13.1069	23.8253	19.3083	2.14171	4.20905

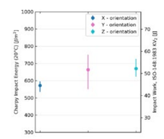
Y / Transverse dir.

	E_mod	yield_S	tensile_S	elong	RA
n	6	6	6	6	6
min	207.045	620.167	698.553	26.6448	75.8412
max	190.981	599.264	671.891	24.6972	70.5843
avg	197.127	608.887	682.981	25.5322	72.644
std	5.63025	6.62476	8.82184	0.783463	1.66157

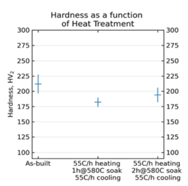
Z / Build dir.

	E_mod	yield_S	tensile_S	elong	RA
n	5	5	5	5	5
min	205.581	593.223	683.706	28.0907	78.2195
max	181.015	545.22	635.139	22.2763	70.5843
avg	193.701	576.693	667.736	24.4683	74.709
std	8.41539	19.5277	19.4796	2.12705	2.50047

E_mod: Elastic modulus [Gpa]
yield_S: 0.2% Yield Strength [MPa]
tensile_S: Ultimate tensile strength [MPa]
elong: Elongation at fracture [%]
RA: Reduction of area [MPa]



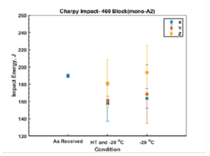
Charpy values for three different directions for sample N-1200 in as-received condition

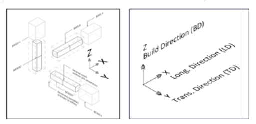


	A1_ADD	BD205T	BD206T
AVG	212.00	182.00	194.11
STD	15.37	7.77	11.90
Min	26.00	14.00	19.11
Max	-69.00	19.00	20.89

A1_ADD: As-built condition
BD205T: 1h soak @580C
BD206T: 2h soak @580C
[HV2]

Hardness for as-received and heat treated conditions of the AM46 (N-1200) printed block





AM46 Impact energy for different directions and conditions

	Post-Weld heat treatment	Testing condition
As-received	None	Room temperature
HT and -20C	55C/h warm-up, 1h soak @ 580C, 55C/h cool-down	-20C (cooled down with liquid nitrogen)
-20C	None	-20C (cooled down with liquid nitrogen)

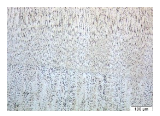
X-Orientation	n	AVG	STD	MIN	MAX
As-Received	3	189.7	1.6	188.4	192.0
HT and -20C	2	157.9	14.8	143.1	172.6
-20C	3	163.5	9.4	150.3	171.5

Y-Orientation	n	AVG	STD	MIN	MAX
As-Received	0	-	-	-	-
HT and -20C	3	161.0	4.1	155.8	165.9
-20C	2	168.5	24.1	144.4	192.5

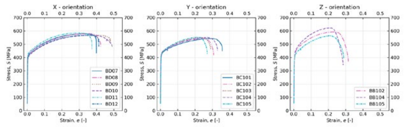
Z-Orientation	n	AVG	STD	MIN	MAX
As-Received	0	-	-	-	-
HT and -20C	2	196.1	4.6	191.5	200.6
-20C	3	193.5	25.8	162.3	225.5

AM46Charpy Impact test results for samples under the indicated conditions

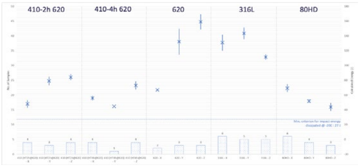
AM316L



Microstructure of AM316 printed part showing a dendritic solidification structure.

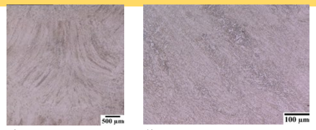


stress-strain curves for printed AM316L in three orientations



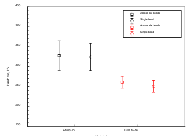
Charpy impact data for several printed materials including heat treatments in different directions

AM80HD

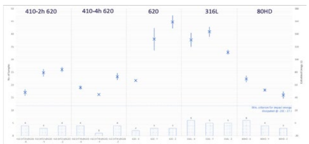


a) b)

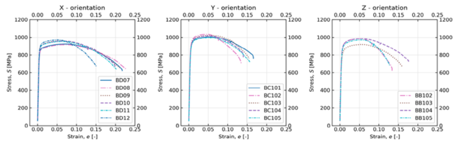
a) the microstructure of a AM80HD bead indicating the columnar solidification weld metal structure and adjacent coarse grain HAZ, b) microstructure at higher magnification.



Hardness data of AM80HD, left side of the graph



Charpy impact data for several printed materials including heat treatments in different directions

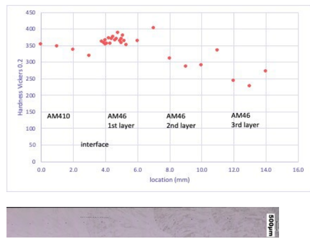


Stress-strain curves for printed AM80HD in three orientations.

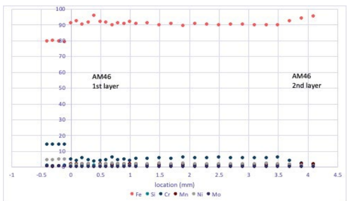
Bi-Material blocks

AM46 printed on AM410

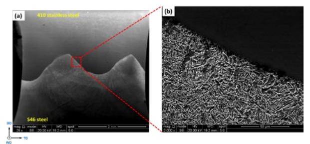
Macrograph of the interface between AM410 to AM46



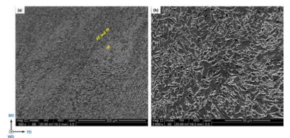
a) Hardness across the interface from AM410 to AM46, b) macrograph indicating hardness locations and interface.



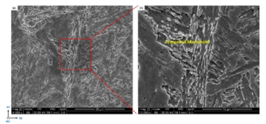
chemical composition from 1st deposit AM410 to AM46, interface at x=0



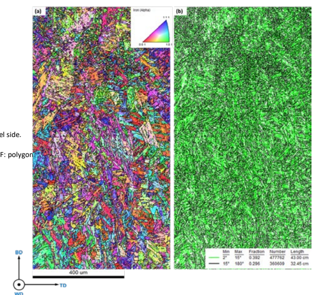
The SEM images of S46 steel- AM410 stainless steel bi-material (a) Low magnification SEM-SE image showing the interface (b): Higher magnification of the selected red rectangular in Fig. 1a



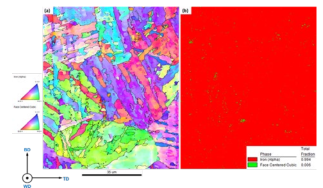
The SEM-SE images of different grains having different microstructures, which have been formed during solidifications on the side of S46 steel (M: martensite, AF: acicular ferrite, and PF: polygon



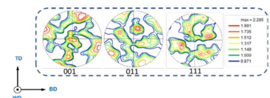
SEM-SE images showing the tempering of martensitic structure on 410 stainless steel side.



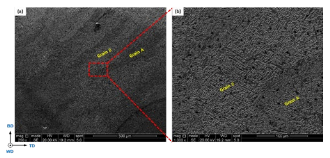
Some EBSD results from the 410 stainless steel side (a): BD-IPF map, (b): The grain boundaries distribution map.



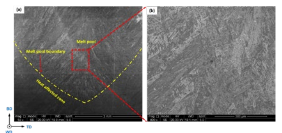
Some results of high-resolution EBSD data with the step size of 70 nm for 410 stainless steel.



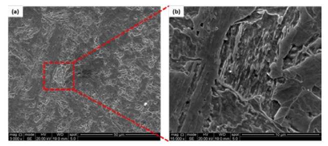
Different pole figures of martensite structure on the side of 410 stainless steel.



The microstructure of different grans which have formed during solidifications in side of S46 steel.



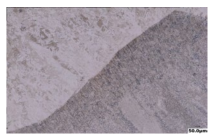
The microstructure of 410 stainless steel.



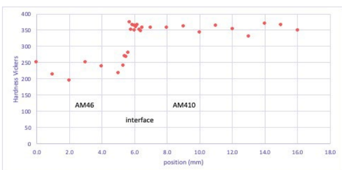
The microstructure of the heat-affected zone, which is just below the melt pool.

AM419 printed on AM46

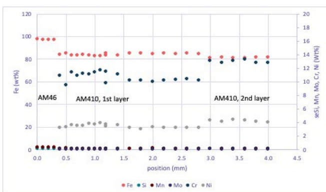
Macrograph between AM46 and AM410, indicating several layers of AM410



Micrograph at interface between AM46 and AM410

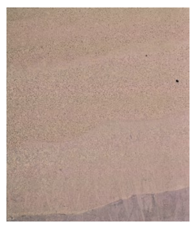


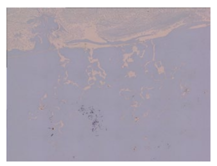
Hardness across the interface from AM46 to AM410

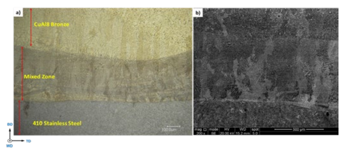


Elemental composition from 1st deposited AM46 to AM410

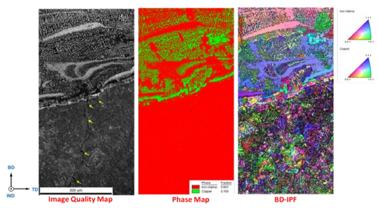
CuAl8 printed on AM410





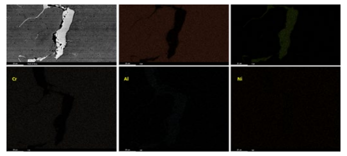


The microstructure of interface region for AMCuAl8 bronze - AM410 stainless steel bi-material (a): optical microscopy image, (b): SEM-SE image

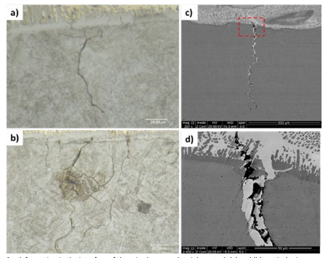


interface AM410 to CuAl8 indicating 1st deposit of CuAl8, indications of liquid metal embrittlement and cracks, inhomogeneous mixing at the interface

interface AM410 to CuAl8 indicating 1st to 4th deposit of CuAl8, indications of liquid metal embrittlement and cracks, inhomogeneous mixing at the interface



The EDS map for a crack that has been formed in the heat-affected zone (HAZ) of AM410 stainless steel.



Crack formation in the interface of the mixed zone and stainless steel; (a) and (b): optical microscopy images, (c) and (d) SEM-BSE images.

Some EBSD results across the interface of AM410 stainless steel and mixed zone.

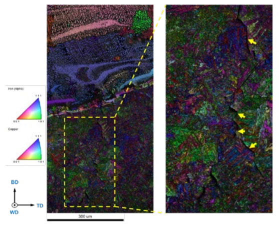
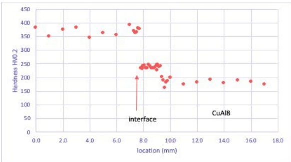
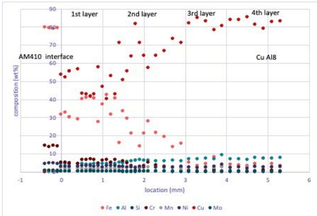


Image quality + BD-IPF maps for the interface between AM410 stainless steel and the transition zone.



Hardness across the interface from AM410 to CuAl8



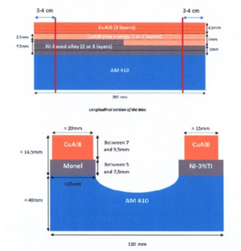
Elemental composition across the interface from AM410 to CuAl8 (wt%)

Table 3.8: Corrosion data for bi-material printed parts.

Sample	*Run*	*OCP $_{12h}$ (mV)*	*E_{corr} (mV)*	*I_{corr} (µA)*	*i_{corr} (µA/cm^2)*	*EW*	*ρ (g/cm^3)*	*CR (mm/yr)*	
*N1221C1**	*1*	*-251,1*	*-222,327*	*0,18*	*0,229*	*26,28*	*7,7*	*0,0026*	AM410 on AM46
N1221C1	*2*	*33,15*	*-53,77*	*0,013*	*0,017*	*26,28*	*7,7*	*0,0002*	AM410 on AM46
*N1221C2**	*1*	*-359,2*	*-346,807*	*2,071*	*2,637*	*26,28*	*7,7*	*0,0294*	AM410 on AM46
*N2151C1**	*1*	*-253,2*	*-264,691*	*3,523*	*4,486*	*38,91*	*7,78*	*0,0734*	CuAl8 on AM410
*N2151C2**	*1*	*-216,5*	*-264,331*	*5,4*	*6,875*	*38,91*	*7,78*	*0,1125*	CuAl8 on AM410

** Crevice corrosion detected*

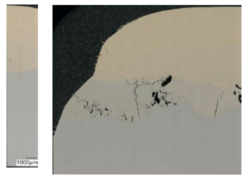
Tri-material blocks



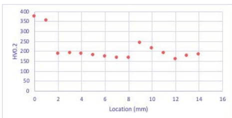
Cross section of the bloc

CuAl8 printed on AM410 with interlayer Monel or Ni+3wt%Ti

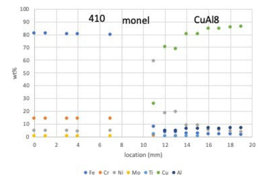
monel



Macrograph of N21_46_51_Monel_CuAl8_4 layers.

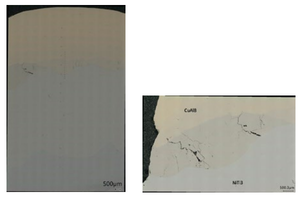


Hardness distribution AM410 - monel - CuAl8

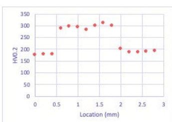


EDS scan across interface AM410-Monel-CuAl8

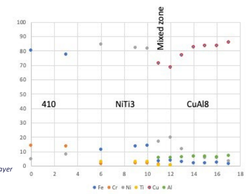
Ni 3wt% Ti



a) Macrograph of N21 46 51 Ni3Ti CuAl8 4 layers, b) enlargement



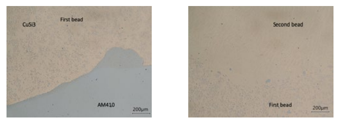
Hardness distribution at interface Ni3Ti-CuAl8 of N21 46 51 Ni3Ti CuAl8 4 layer



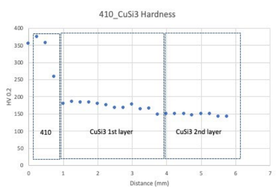
EDS scan across interface AM410-NiTi3-CuAl

Bi-material blocks

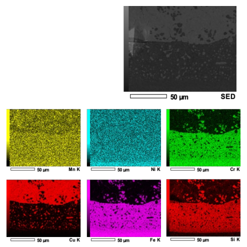
CuSi3 on AM410



a) interface between AM410 and CuSi3, b) interface between 1st and 2nd deposit of CuSi3

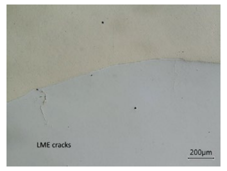


Vickers hardness across interface AM410 - CuSi3.

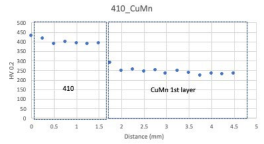


EDS maps of several elements at the interface between AM410 and CuSi3

CuMn13Al7 on AM410



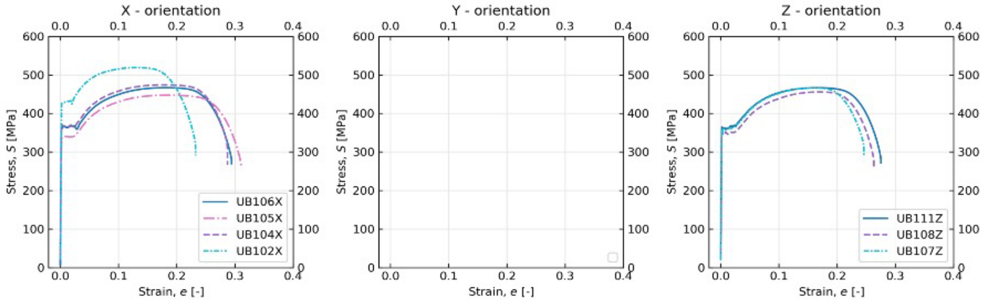
CuMn13Al7 deposited on AM410, indications of LME



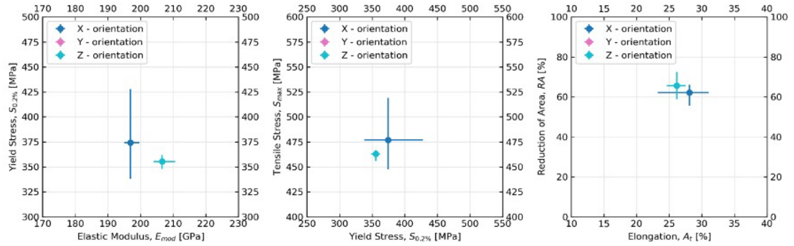
Hardness distribution across the interface between AM 410 and CuMn13Al7

Mould for Bathtub showface Villeroy &Boch, RAMLAB

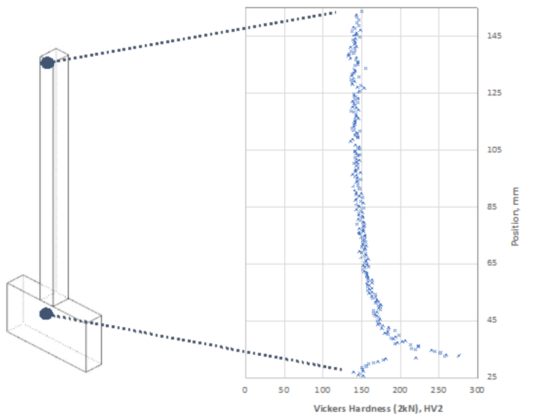
single wall
3D Print AM35



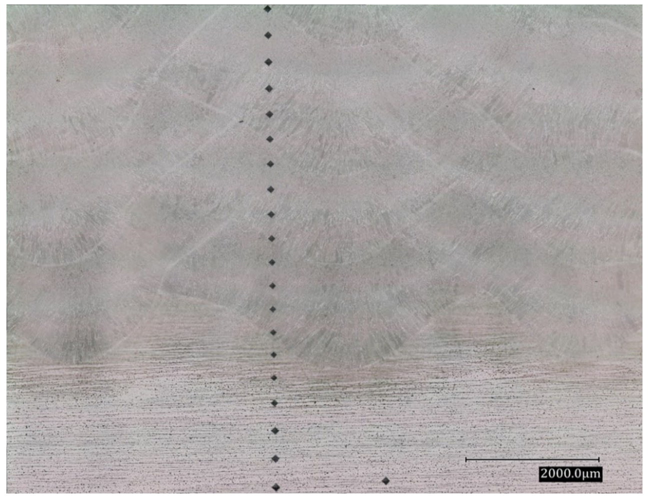
stress - strain curves for the printed AM35 steel in the welding direction (x) and the building direction (z).



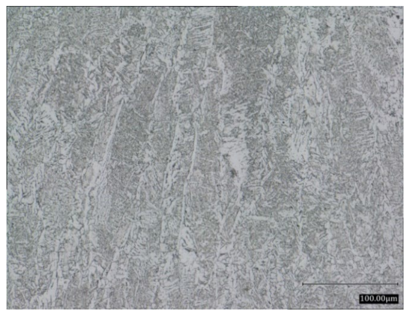
tensile test results for the printed AM35 steel in the welding direction (x) and the building direction (z).

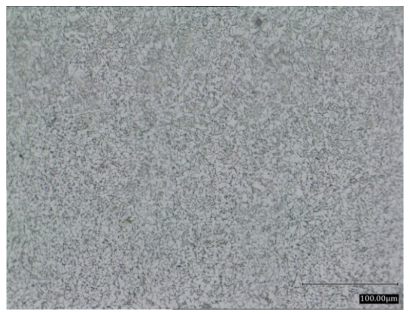


hardness as function of build height



AM35
macrostructure

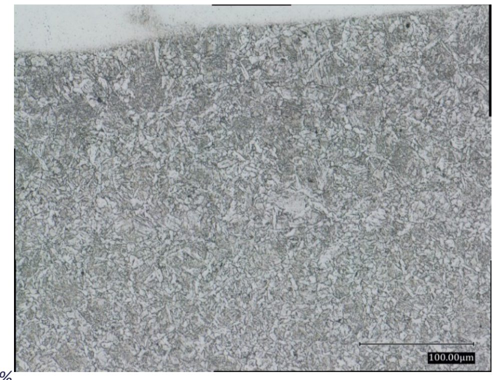




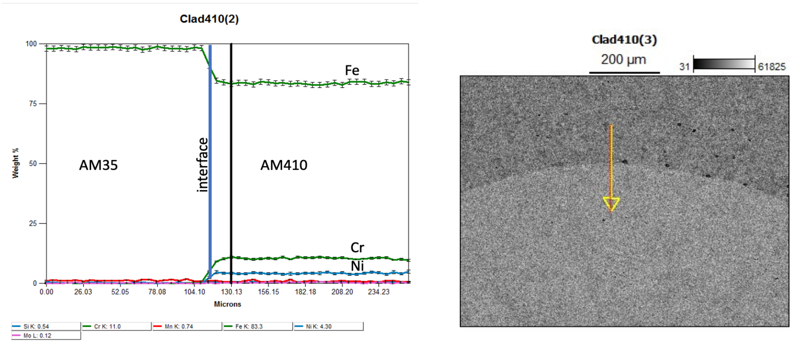
micrographs AM35
a) Columnar solidification structure b) fine grained heat affected zone

Bi material
AM35 - AM410

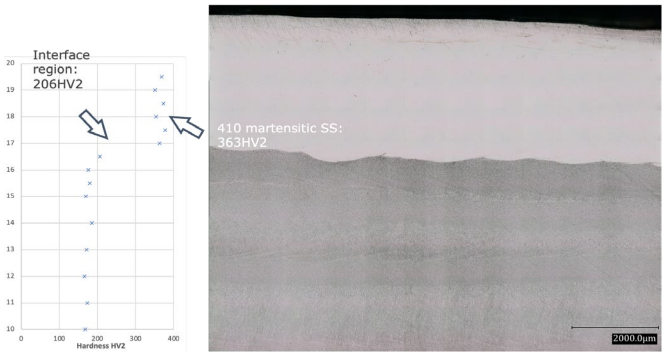
Bi-material block AM35 bottom part and martensitic stainless steel AM410 top part. Interface region without apparent discontinuities, Etchant: Nital 5 %



Interface region, top martensitic stainless steel AM410, bottom fine grained AM35. apparent discontinuities, Etchant: Nital 5%.

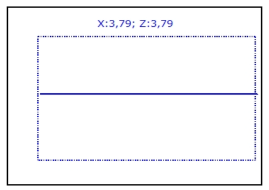


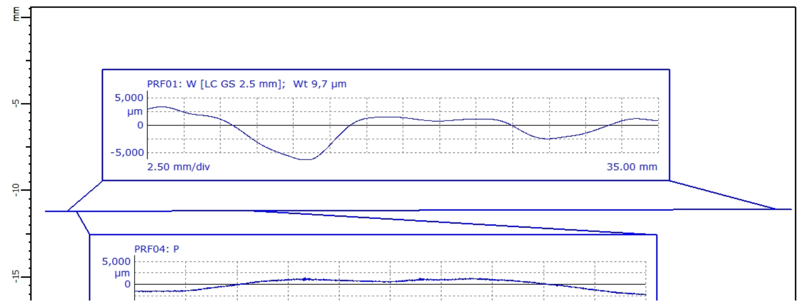
Line scan across interface from AM35 to AM410.

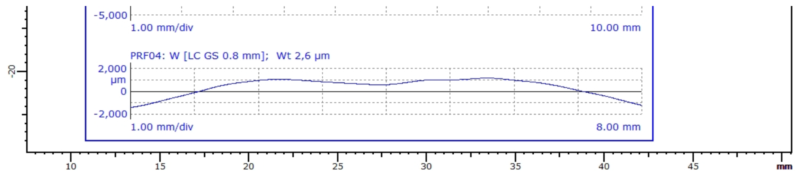


Hardness HV2, along the building direction of coupon R-1121-(PRJ-B1-002

Meas. instrument:	Mahr-MeasCard
Drive unit:	CD 120
Probe:	PCV 350 / 33 mm
Lt:	42.29 mm
Ls:	-,--
VB:	+/-25000.0 µm
Vt:	0.20 mm/s
Points:	42283



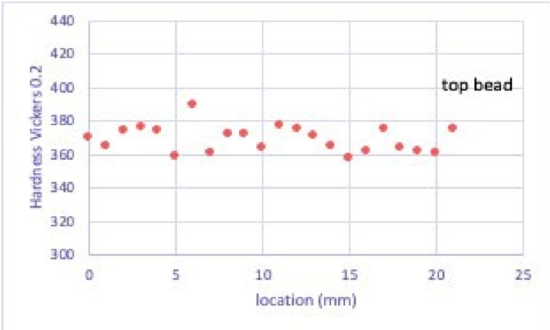


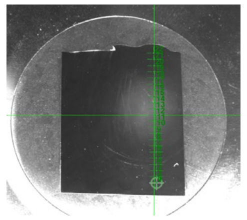


Roughness profile of polished sample surface

Alternative top-facing materials

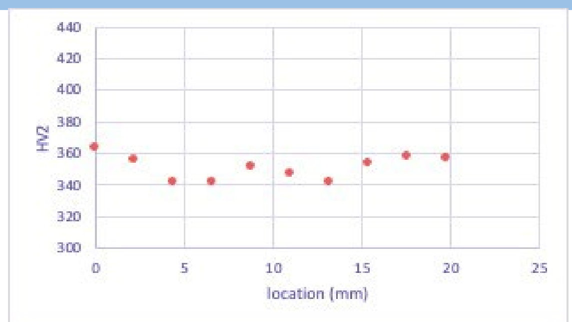
3Dprint AM410NiMo





Cross sectional micrograph of AM410NiMo, untreated.

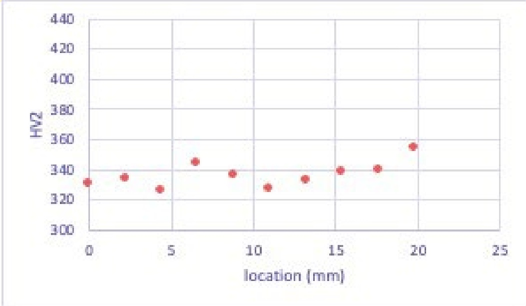
3Dprint AM410NiMo: heat treated



Hardness measurements in the build direction. 0 represents the top surface, heat treated

micrograph of heat treated 3Dprint AM410NiMo

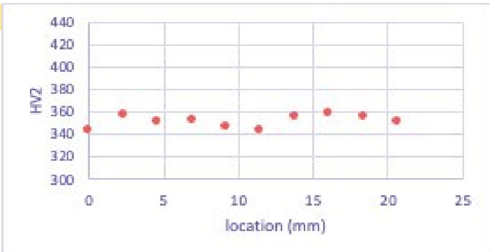
Thermanit16/05 Mo



Hardness measurements in the build direction, location 0 is at the top surface. average 336 $HV_{2.0}$, st dev 8.4 $HV_{2.0}$, untreated

Micrograph of Thermanit16/05 Mo, untreated

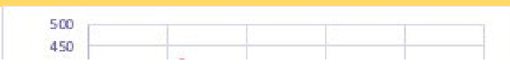
Thermanit16/05 Mo
heat treated

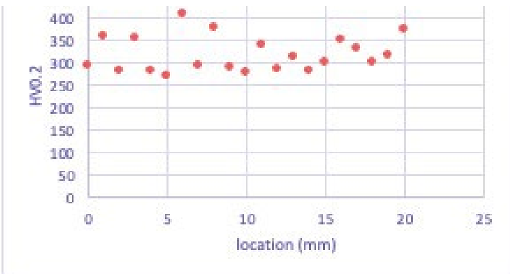


Hardness measurements in the build direction, location 0 is at the top surface, heat treated

Micrograph of cross section, heat treated.

UTP Dur250

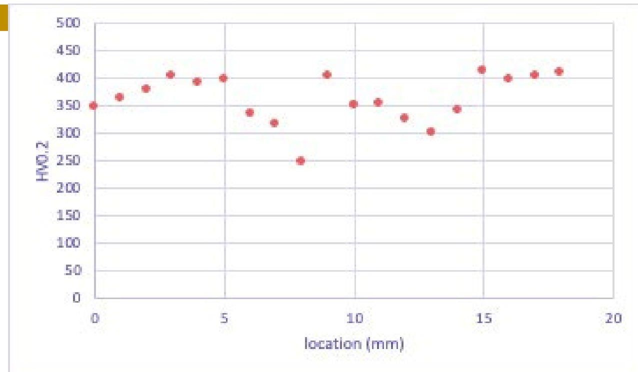




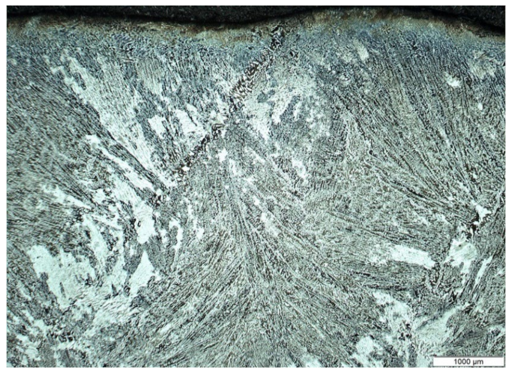
Microhardness in printed block UTP Dur250, top at location 20 mm

micrograph of top layers, UTP Dur250

SKWAM -IG



Microhardness as function of location, top layer is at 20 mm

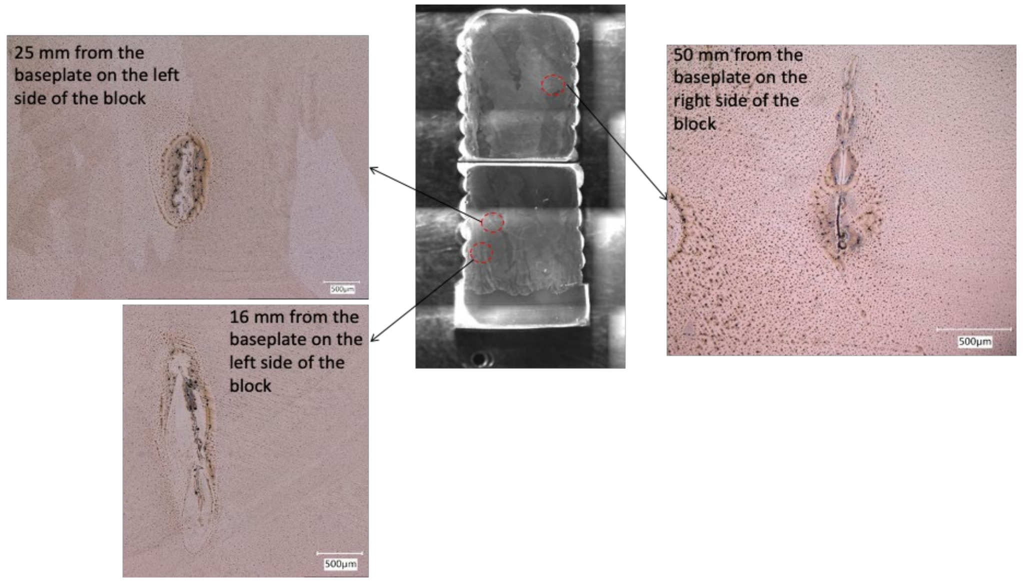


macrographs of Bohler SKWAM-IG, Inomaxx® Plus *gas shielding*

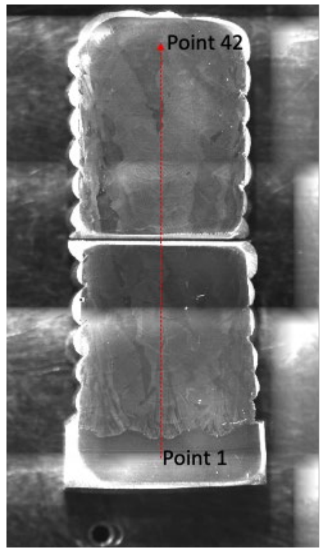
B2 **Mandrel tool for GKN Aerospace, RAMLAB**

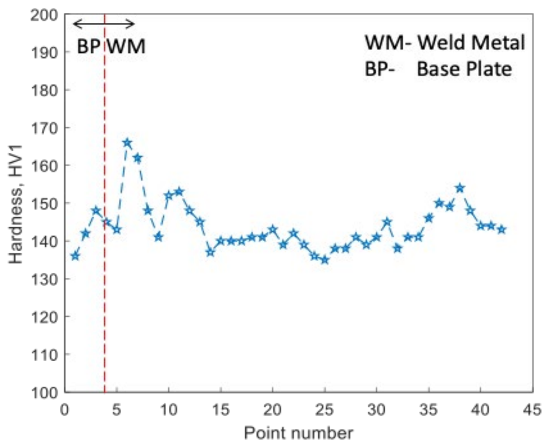
1.3912 - FeNi36

macrographs GMAW



Cross section of FeNi36 block 3
with indications of intergranular cracks



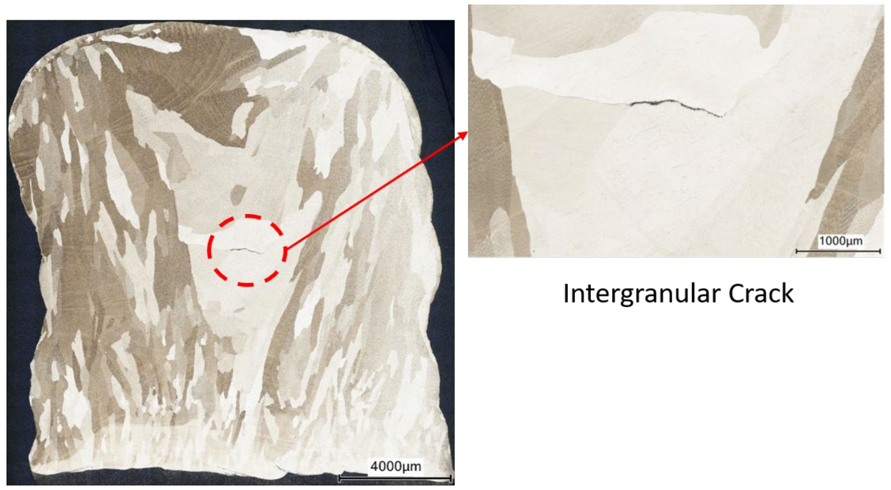


Hardness distribution HV1 along FeNi36 block 3

1.3912 - FeNi36 GTAW

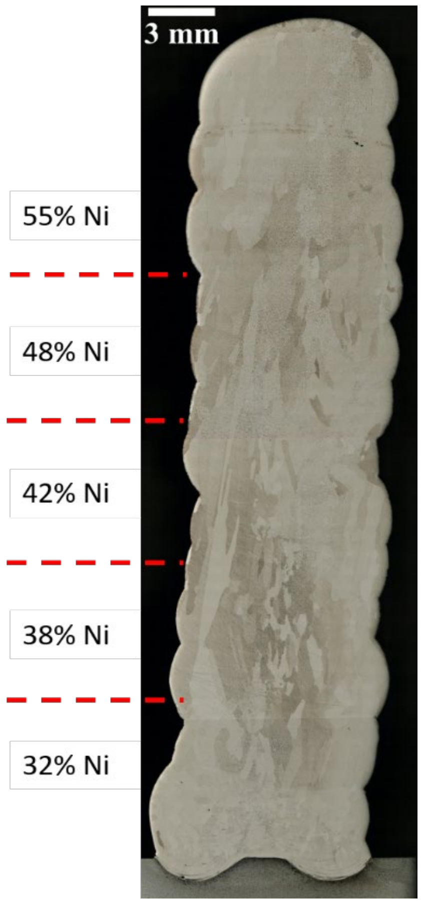
a) b)

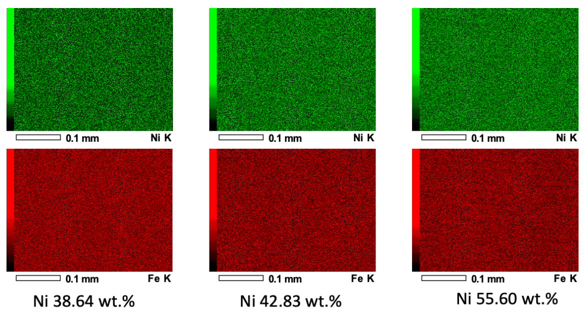
:two examples of cross section of FeNi36 deposits a) I= 130 A, v_{travel} = 4.6 mm/s, v_{wire} = 21.7 mm/s, heat input 200 J/mm, b) I= 218 A, v_{travel} = 3.3 mm/s, v_{wire} = 49.4 mm/s, heat input 550 J/mm



a) b)

a) construct welded with low heat input 200 J/mm, b) construct welded with high heat input 550 J/mm, showing an intergranular crack





b)

a)

a) Graded FeNi wall, b) EDS measurements at bottom, middle and top of the wall showing a homogeneous distribution of Ni and Fe

Coefficient of thermal expansion of FeNi36 plate material. Comparison induction heating, material specification and furnace heating for different temperature ranges. Induction heating TUD, furnace heating at Element (Sweden)

Mean CTE	Induction heating (× 10^{-6} °C^{-1})	Material specification (× 10^{-6} °C^{-1})	Furnace heating (× 10^{-6} °C^{-1})
20-100 °C-	2.04	1.30	1.36
20-149 °C-	2.50	2.11	2.01
20-260 °C-	5.12	4.18	4.67
20-360 °C-	8.21	7.60	7.57

Coefficient of thermal expansion of FeNi 36 plate material, furnace heating conducted at UTwente and at Elements, for different temperature ranges

Mean CTE	UTwente (× 10^{-6} °C^{-1})	Elements (× 10^{-6} °C^{-1})
RT-100 °C-	1.33	1.36
RT-200 °C-	2.69	2.70
RT-300 °C-	5.84	6.01
RT-400 °C-	8.36	8.63
RT-500 °C-	10.14	10.32

Coefficient of thermal expansion of FeNi 36 printed material for a heat input of 200 J/mm and 550 J/m for samples in the building direction (vertical) and the printing direction (horizontal). Furnace heating carried out at UTwente

Mean CTE	200 J mm^{-1} Vertical (× 10^{-6} °C^{-1})	200 J mm^{-1} Horizontal (× 10^{-6} °C^{-1})
RT-100 °C-	1.40	1.39
RT-200 °C-	2.74	2.67
RT-300 °C-	5.85	5.73
RT-400 °C-	8.34	8.15

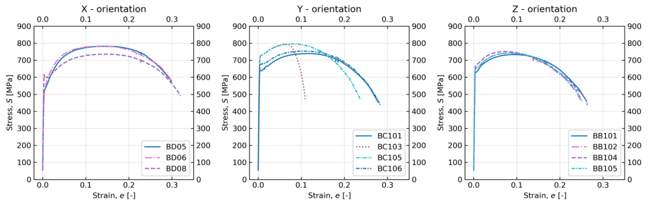
Mean CTE	550 J mm^{-1} Vertical (× 10^{-6} °C^{-1})	550 J mm^{-1} Horizontal (× 10^{-6} °C^{-1})
RT-100 °C-	1.48	1.27
RT-200 °C-	2.79	2.60
RT-300 °C-	5.92	5.81
RT-400 °C-	8.32	8.36

B3

Moulding tool for Shapers, NAVAL Group

Monoblock of AM62

tensile tests



charpy impact tests

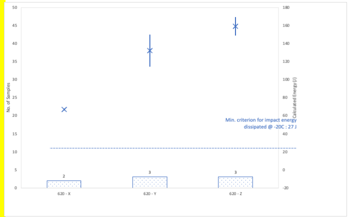


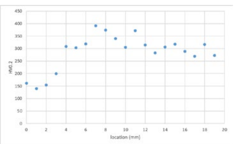
Table 6.1: Corrosion test data for printed AM62, CR is corrosion rate.

Sample	***Run***	***OCP $_{12h}$ (mV)***	***E_{corr} (mV)***	***I_{corr} (μA)***	***i_{corr} (μA/cm^2)***	***EW***	***ρ (g/cm^3)***	***CR (mm/yr)***
N6200C2 (Shapers Sol)	*1*	*-638*	*-571,2*	*8,038*	*10,234*	*28,61*	*7,86*	*0,1218*
N6200C2 (3.0wt NaCl)	*2*	*-636*	*-573,3*	*8,008*	*10,196*	*28,61*	*7,86*	*0,1214*

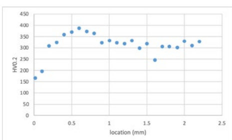
Bi-material blocks

LNM NiFe + LNM MoNi

hardness



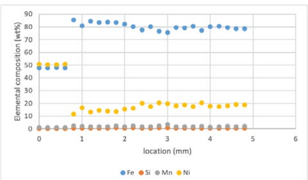
a



b

c

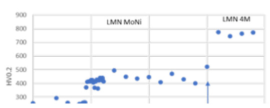
Hardness across the interface from LNM NiFe to LNM MoNi, a) along line A in figure 6.3c, b) along line B in figure 6.3c, c) location of indents across interface.



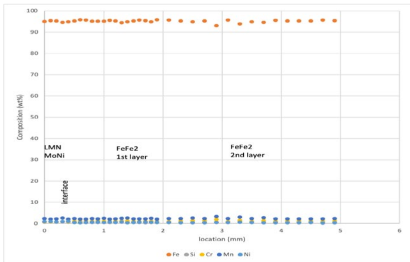
Elemental composition across interface

: Macrograph of the interface LNM NiFe (bottom)- LNM MoNi (top). Indications of cracks

LNM MoNi + LNM 4M



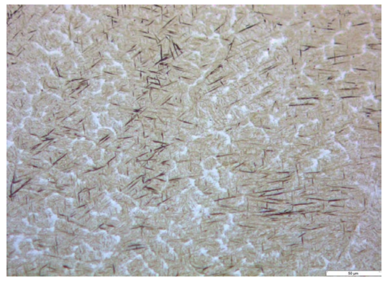
Hardness across the interface from LMN MoNi to LMN 4M, interface



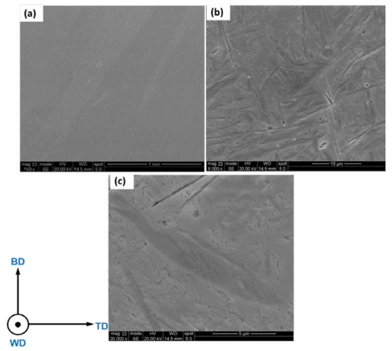
Chemical composition across the interface LMNMoNi -LNM 4M (FeFe2

Macrograph bottom layers LNM MoNi , top layers LNM 4M (Fe-Fe2)

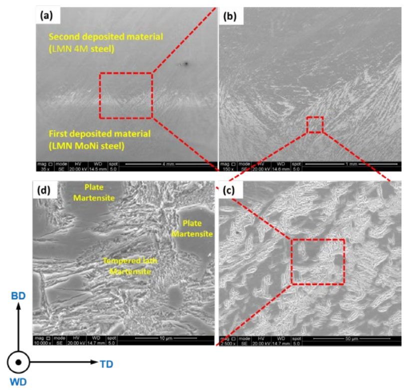
Micrograph detail of interface LNM MoNi - LNM 4M



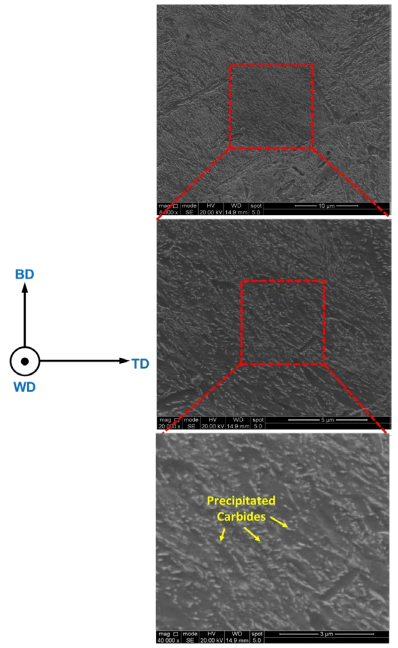
Micrograph top layer LNM 4M



The microstructure of top layer of deposited LMN 4M steel, SEM-SE images in different magnifications



The microstructure of the interfacial region between LMN MoNi and LMN 4M steels; SEM-SE images in different magnifications



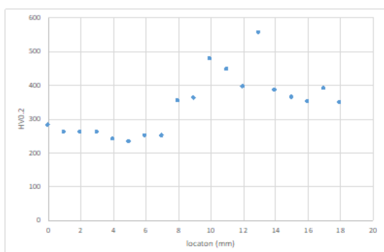
SEM-SE images showing the microstructure of deposited LMN MoNi steel located in the middle region of the sample

Tri layer deposit

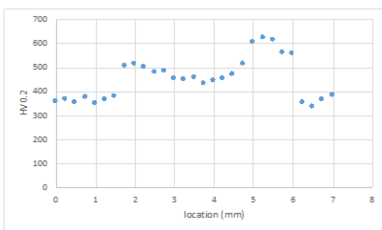
AM62 + FeFe2 + AM62

Macrograph of coupon N-626162 Tri

hardness

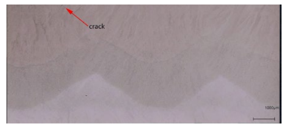


a



b

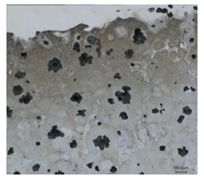
Hardness profile over the cross section, right hand side is top of the sample (AM62), a) global profile, b) local (starting from location 8 mm in a) to 15 mm)



Micrograph of cracks in FeFe2 and mixed zone FeFe2-AM62

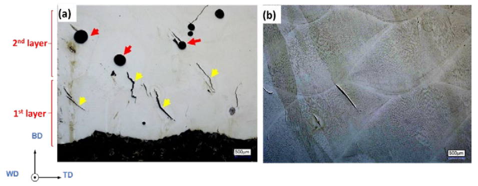
LNM NiFe + cast iron G-500-7

Cross section of the interface between cast iron (bottom) and LNM NiFe (top), showing the distribution of the grafite and defects in the top layer

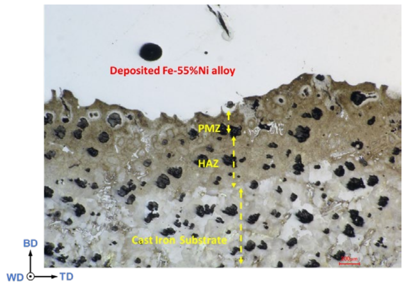


cross section of the interface between cast iron (bottom) and LNM NiFe (top)

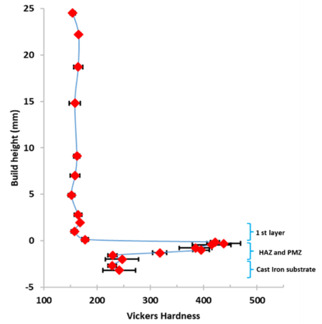
The low magnification optical image of the deposited layers



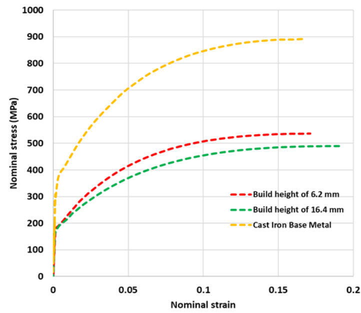
Formation of some defects during fabrication of bimetallic structure in the
(a) first and second deposited layers and (b) following layers



The optical micrograph of the interfacial region between the substrate and deposited alloy



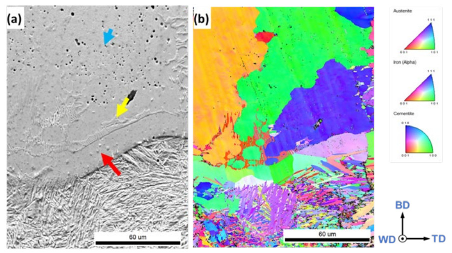
Hardness profile of the bimetallic structure



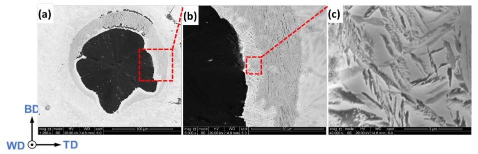
Nominal stress-strain curves generated from the PIP studies.

Location of the indent	Yield Strength (MPa)	Ultimate tensile Strength (MPa)	Uniform Elongation (%)
Cast Iron-base metal	355	895	17.5
Point 1 on Ni-Fe alloy (height of 6.23 mm)	172	536	17.4
Point 2 on Ni-Fe alloy (height of 16.46 mm)	171	494	20.2
As welded Ni-Fe alloy *	230	400	24

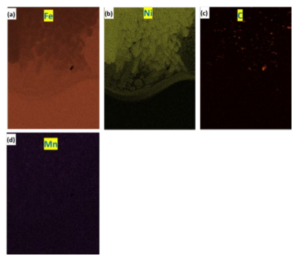
Tensile properties obtained from profilometry-based indentation plastometry (PIP) measurements.



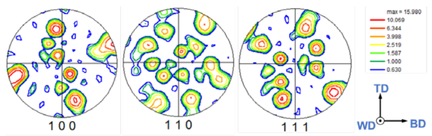
The microstructural change across the interfacial region between PMZ and deposited material (a) SEM image and (b)BD- IPF image from EBSD data



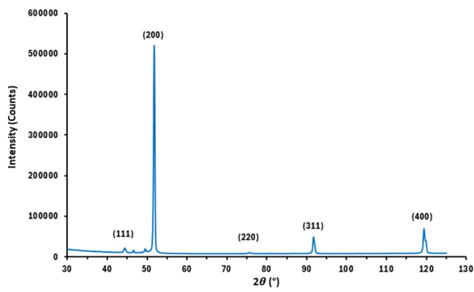
: SEM images of the microstructure around the graphite nodules in PMZ



EDS maps taken from the PMZ/deposited alloy interface



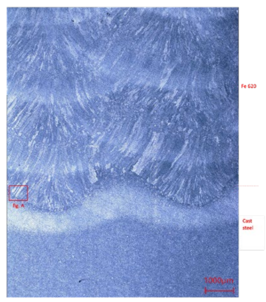
Pole figures related to the deposited Fe-55%Ni alloy.



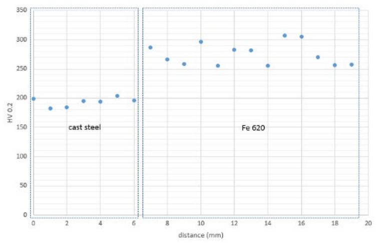
The XRD results for deposited Ni-45% Fe layers

multi material blocks deposits on cast steel

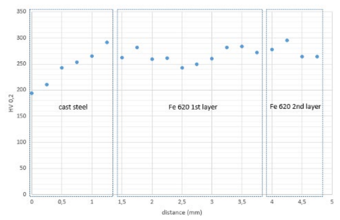
AM62 on cast steel



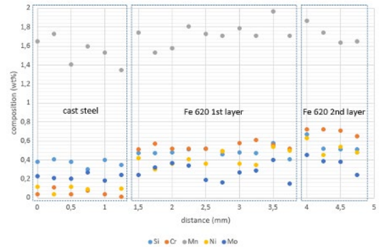
Macrograph of NS562_R



Hardness HV $_{0.2}$ of NS562_R from cast steel through to final layer of Fe 620



Hardness HV $_{0.2}$ of NS562_R of cast steel, first and second layer of Fe 620

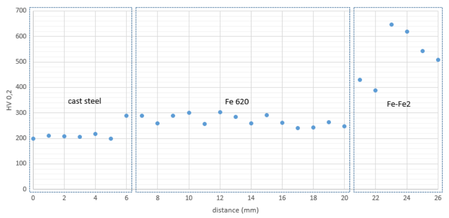


EDS measurements on NS562_R of elements Si, Cr, Mn, Ni and Mo across the interface

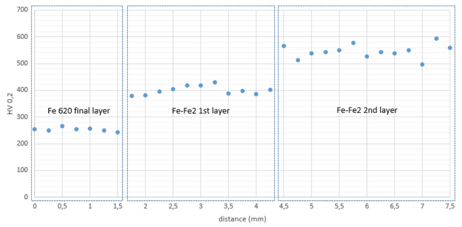
Cast steel + AM62 + FeFe2

Macrograph of NS56261_R

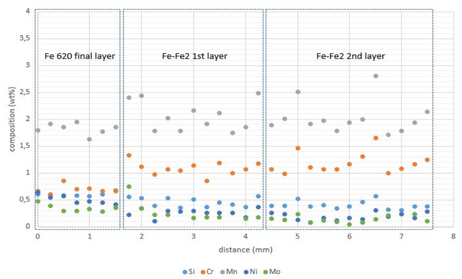
Micrograph of fusion line between first and final layer of Fe-Fe2. Hardness Vickers indents are seen



Hardness of NS56261_R cast steel through to Fe-Fe2

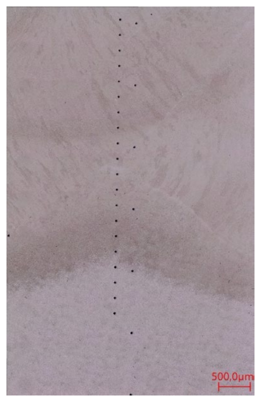


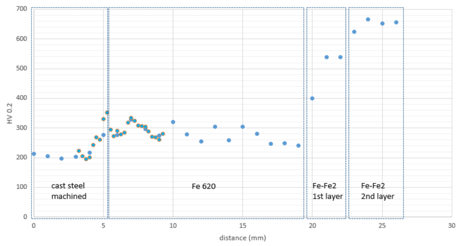
Hardness of NS56261_R Fe 620 final layer through to Fe-Fe2 final layer



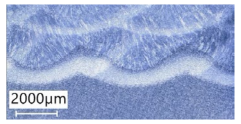
EDS of alloying elements of Fe 620 final layer, and first and second layer of Fe-Fe2

Cast steel + AM62 + FeFe2 interpass milling between diffenrent deposited materials



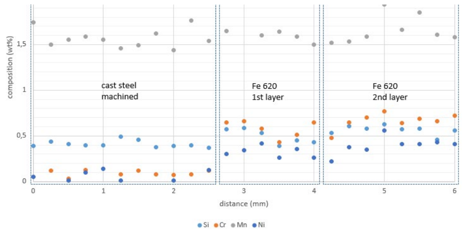


NS56261_M hardness.



Macrograph of NS56261_M

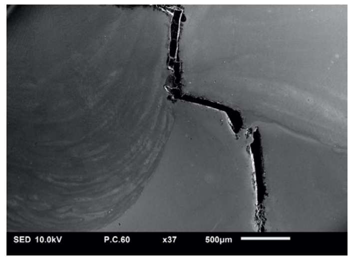
Micrograph of NS56261_M



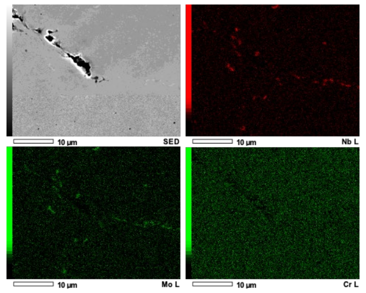
NS56261_M EDS of elements Si, Cr, Mn, and Ni.

Cast steel, Inconel 625 + AM62 + Fe-Fe2

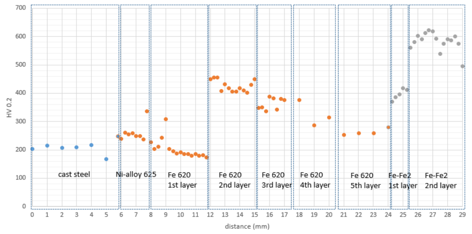
Macrograph of NS5826261_R



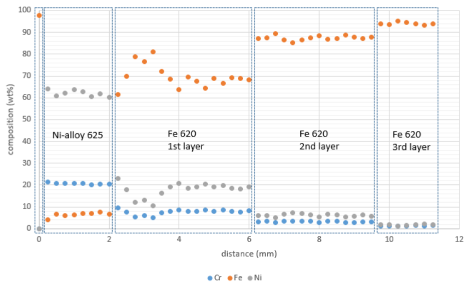
SEM-micrograph of crack in Fe 620 along fusion boundaries and in the weld beads



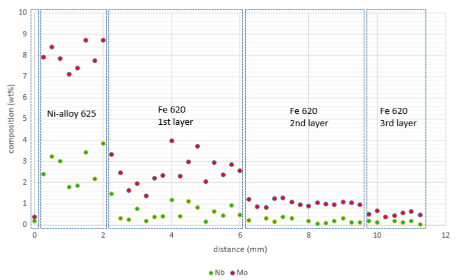
EDS mapping of elements Nb, Mo, and Cr in the area surrounding a crack in Fe 620 show segregation of Nb and Mo



NS5826261_R hardness



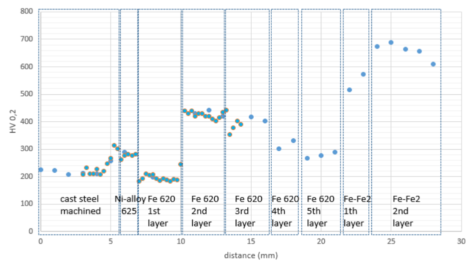
NS5826261_R EDS of elements Cr, Fe, and Ni. Fe 620 1st layer shows an irregular distribution of elements



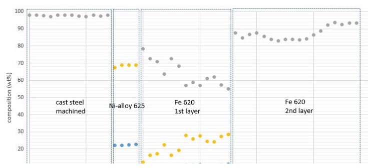
NS5826261_R EDS of elements Nb and Mo

cast steel machined, Inconel 625 AM62 + Fe-Fe2

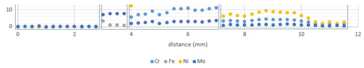
Micrograph of cracks in NS5826261_M



Hardness of NS5826261_M



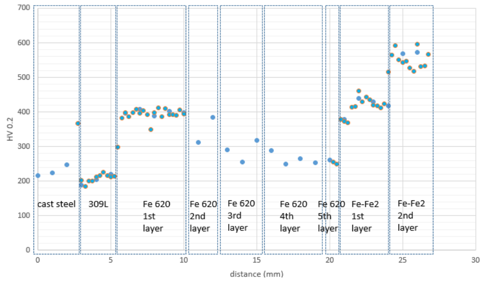
: Macrograph of NS5826261_M



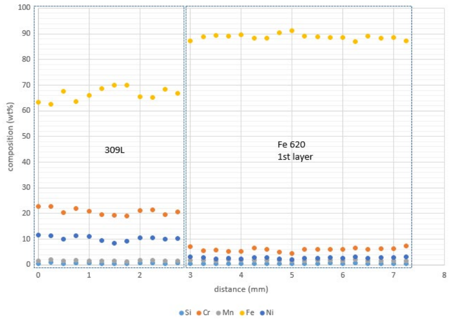
EDS of NS5826261_M

cast steel _AISI309L + Fe620 + Fe-Fe2

Macrograph of NS5916261_R

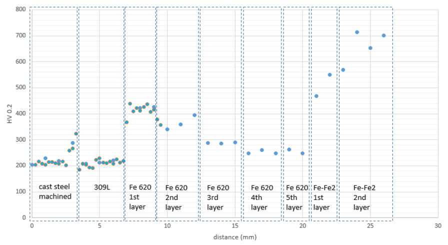


: Hardness of NS5916261_R

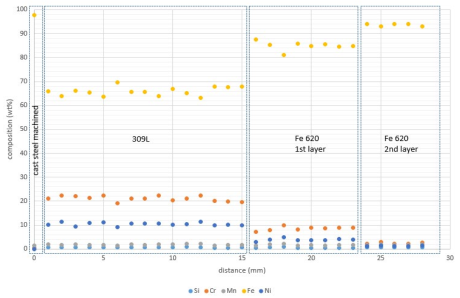


EDS of NS5916261_R of elements Si, Cr, Mn, Fe, and Ni

cast steel _AISI309L + Fe620 + Fe-Fe2 machined



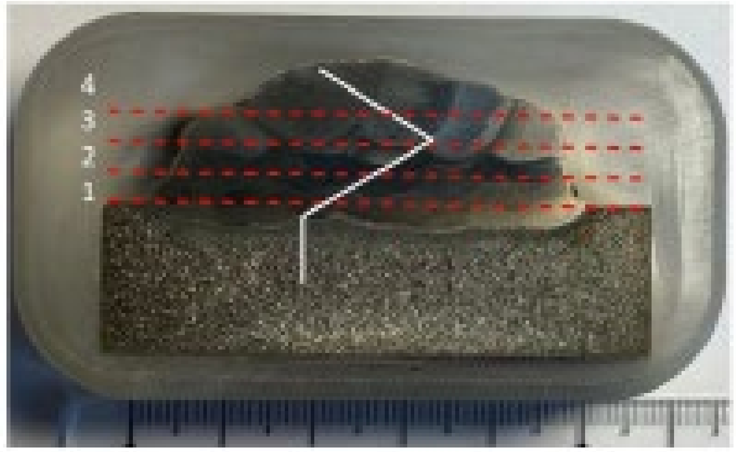
Hardness of NS5916261_M

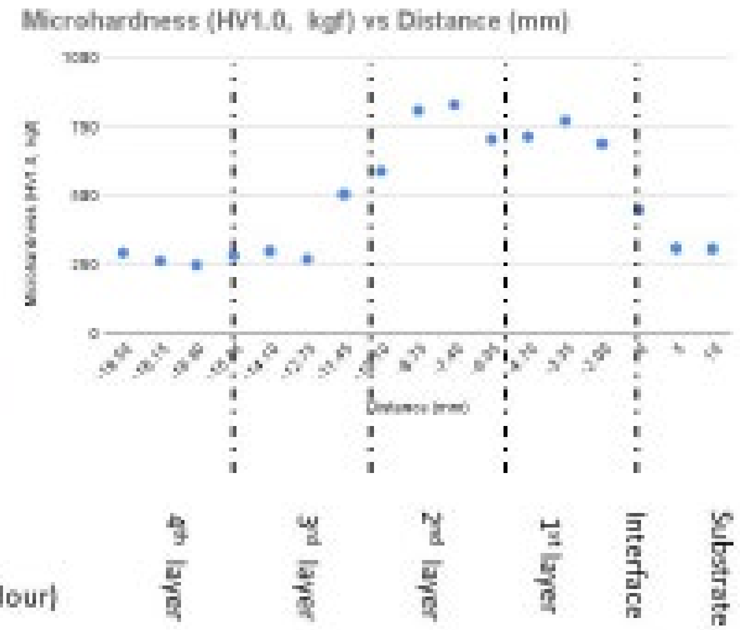


EDS results of NS5916261_M of elements Si, Cr, Mn, Fe and Ni

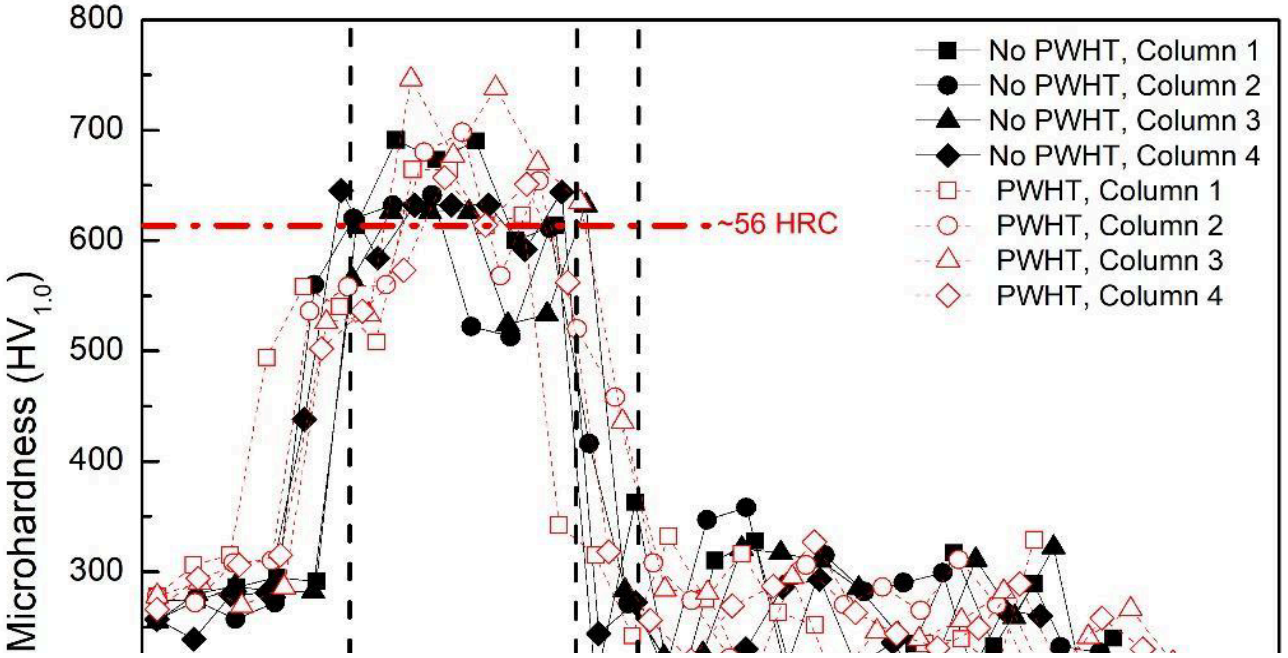
B4 **Forming die for Gorenje Orodjarna, RAMLAB**

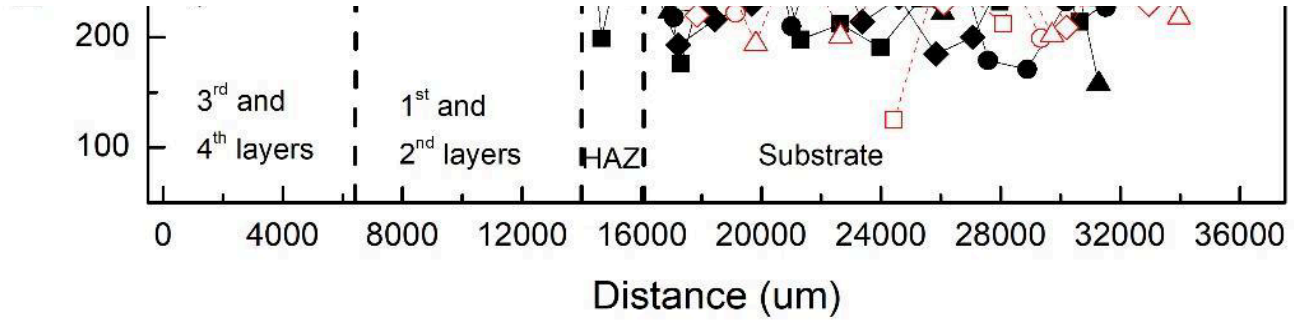
AM Fe4MC1 deposited on the GGG70L steel



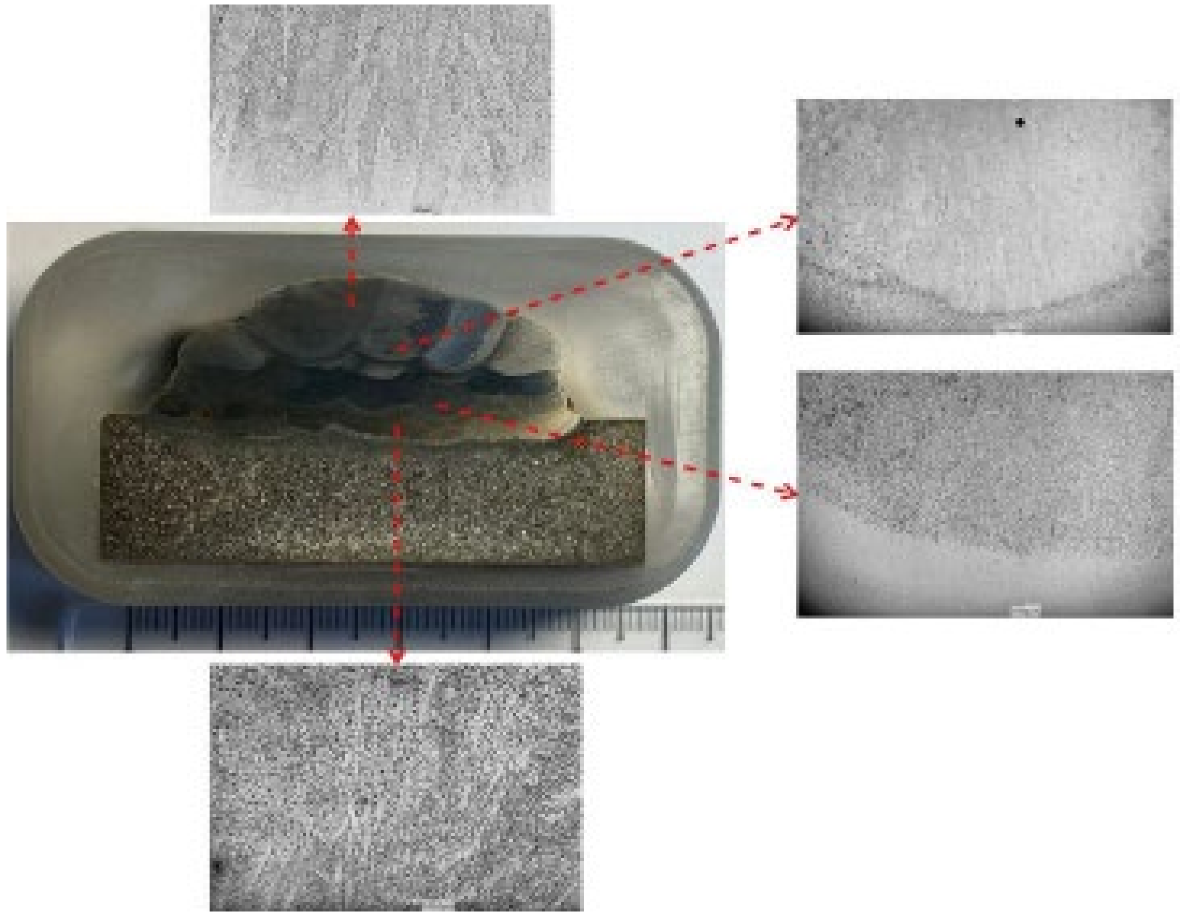


- No preheating
- 3 layers were deposited on cast iron substrate
- Interpass temperature > 300 Deg.C
- Microhardness measured in zig-zag shape (mark white colour)
- Fresh deposit have hardness around 28 HRC (~275 HV)
- Following deposits post heat treated on previous deposit and hardness reach around 60 HRC (~750 HV)





a) indication of the hardness measurement pattern; b) hardness measurements of the as weld and after PWHT of AMFe4MC1 (GRADE 2XLB4-05) deposit on GGG70L



Overview and micrographs of the deposited sample.

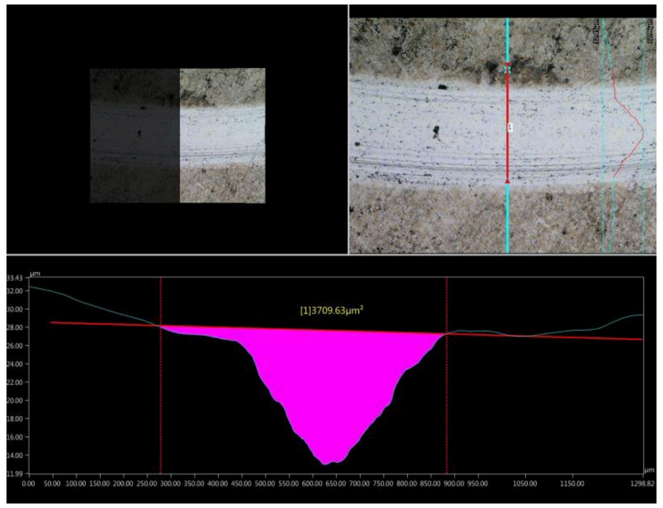
B5 **Forming die for stainless steel parts for Gorenje Orodjarna, RAMLAB**

material	Base material 1.2312 / cladded with patented Aluminium Bronze P20	copper aluminium iron flux core wire CuAl13,5Fe4,0 or alternative material to be specified by LSW

Base material 1.2312/patented Aluminium Bronze

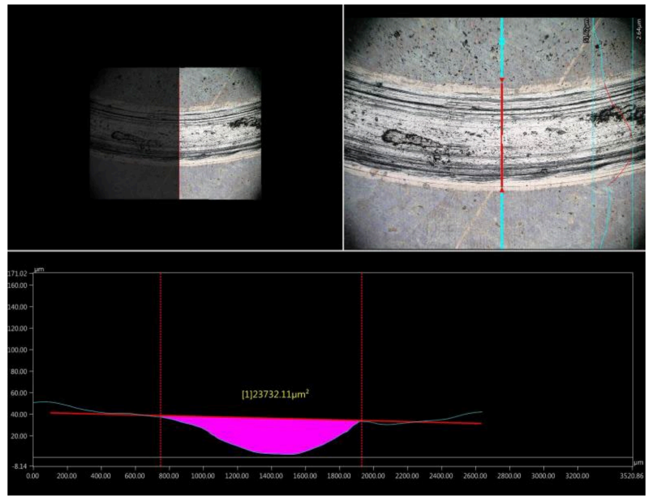
Hardness			
Meritev/ *Measurement*	***Vz.1 / B5*** *Sample Hardnes s[HRc]*	***Vz.2 / B4-1*** *Sample Hardnes s[HRc]*	***Vz.3 / B4-2*** *Sample Hardnes s[HRc]*
1	*23,60*	*23,20*	*18,30*
2	*24,30*	*27,30*	*20,50*
3	*22,20*	*13,00*	*17,20*
4	*23,00*	*11,10*	*20,10*
5		*26,70*	
Average	***20,26***	***23,28***	***19,03***
Required	*36,30*	*56,00*	*56,00*

Hardness measurements of B5 sample, ISO 24373 - S Cu 6338 (CuMn13Al8Fe3Ni2) expected hardness 220 HB according technical data sheet which is roughly 20 HRC



Top view tested samples and profile of the wear, a) AMPCO25

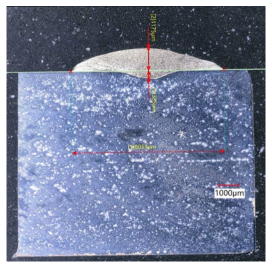
Sample 1 (patented Aluminium Bronze)
Test 1: 75.92 +/-4.05 * 10-6 mm3/N.m (6 mm radius)
Test 2: 77.44 +/-3.70 * 10^{-6} mm3/N.m (8 mm radius)



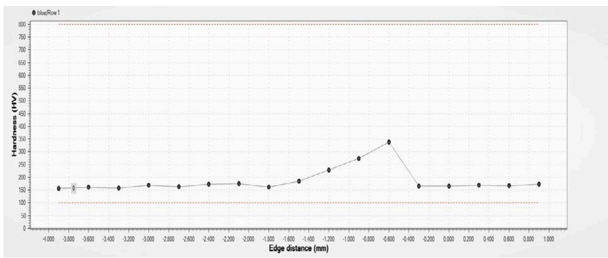
Top view tested samples and profile of the wear, b) ISO 24373 - S Cu 6338 (CuMn13Al8Fe3Ni2) .

Sample 2 (S Cu 6338)
Test 1: 316.16 +/-59.70 * 10-6 mm3/N.m (radius 6 mm)
Test 2: 120.94+/-40.81 * 10-6 mm3/N.m(radius 8 mm)
Test 3: 163.70 +/-39.04 * 10-6 mm3/N.m

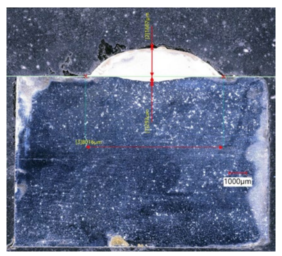
S355 + ASME SFA 5.7 Class ER CuAl-A2 (buffer) + copper aluminium iron flux core wire CuAl13,5Fe4,0

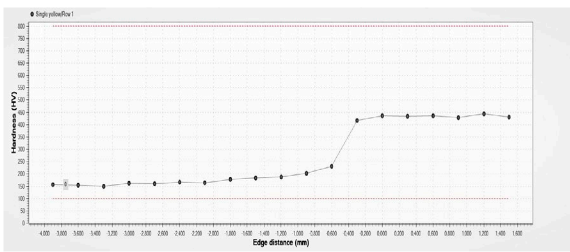


S355 steel plate, + buffer material

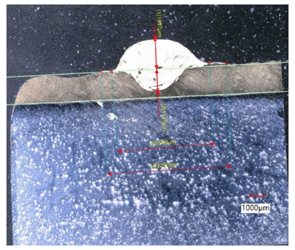


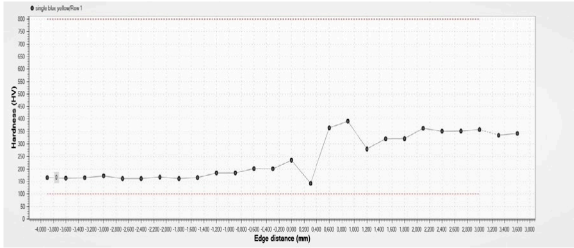
hardness



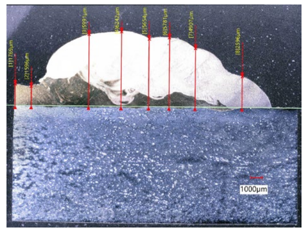


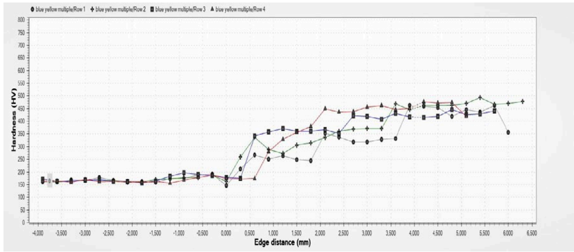
S355 steel plate, + hard-facing material hardness



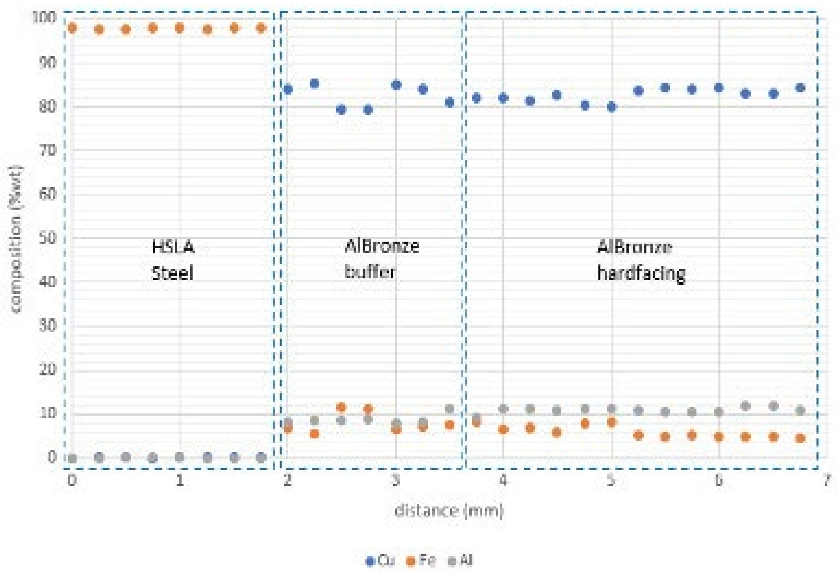


S355 steel plate, + buffer material + 1 layer hard-facing material hardness

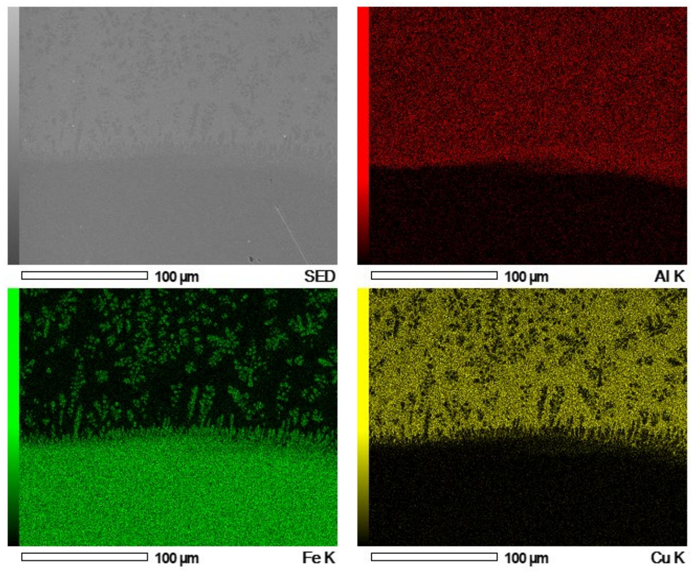




S355 steel plate, + buffer material + 2 layer hard-facing material hardness



EDS measurements of Cu, Fe and Al on the sample containing S355, buffer layer and hard-facing layer



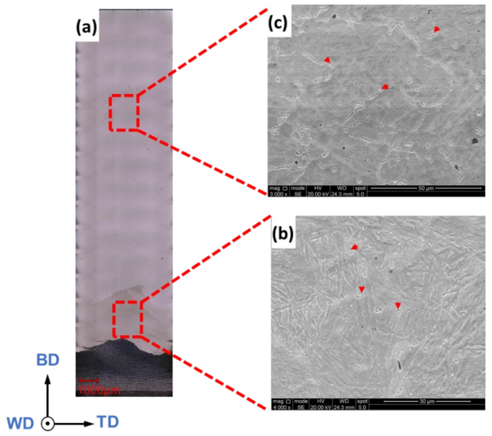
EDS area scans at the interface S355 and buffer layer

B6 Forging die for Kuźnia Jawor, RAMLAB

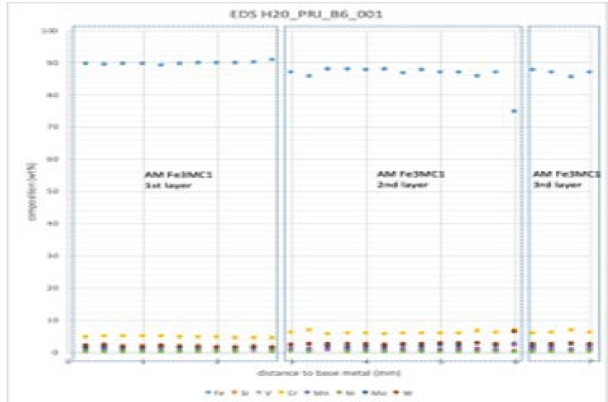
Bi Material Block

Fe3MC1-S355

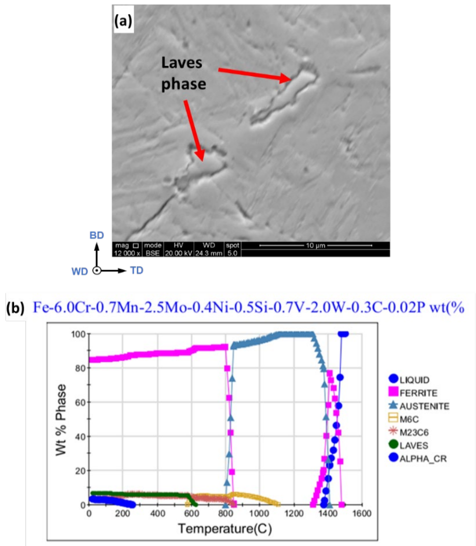
The printed H20-PRJ-B6-001 coupon

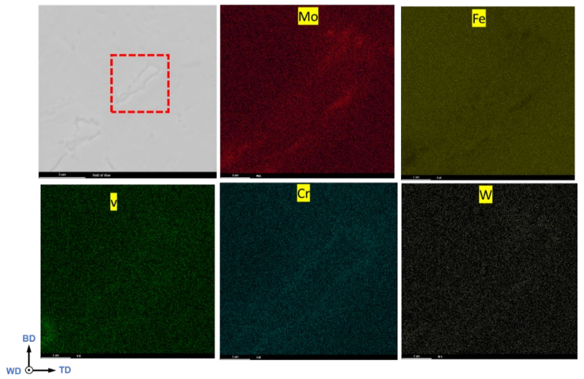


(a) The macrostructure of deposited Fe3MC1 alloy, (b) The SEM image of the first deposited layer and (c) The SEM image of the following deposited layers

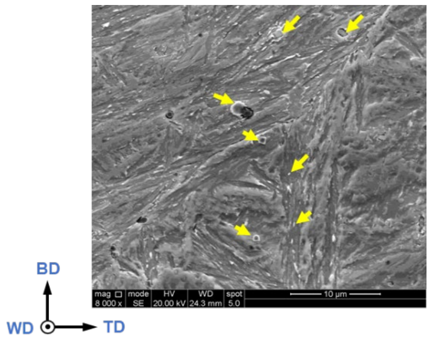


Composition along building direction from 1st layer of Fe3MC1 (TUD



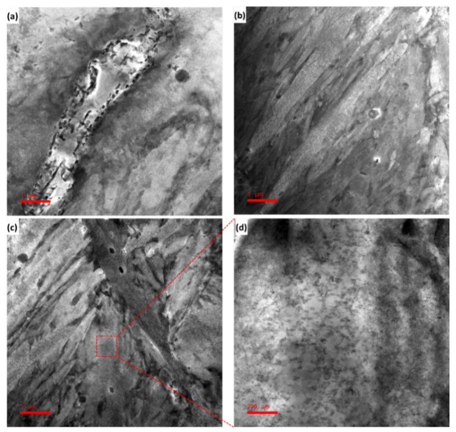


The EDS map of the precipitated Laves phase

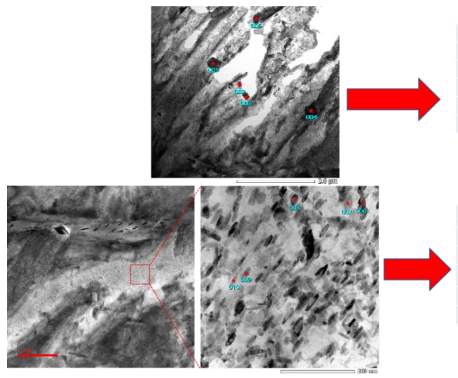


SEM image showing the formation of fine precipitates in Fe3MC1 alloy.

Formation of Laves phases in deposited Fe3MC1 alloy, (a): SEM image and (b) analyses of the solidification path using the JMat-Pro software.



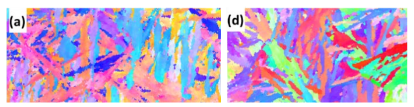
STEM images of carbide precipitation in the martensitic structure of deposited Fe3MC1 alloy.

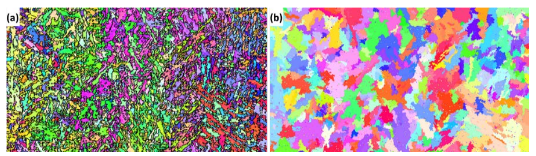


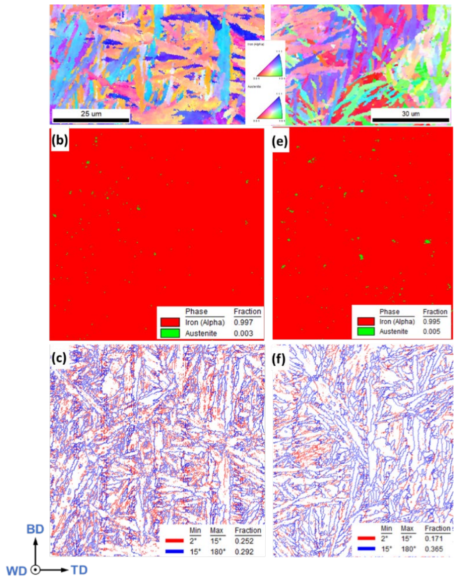
Points	Ti	V	Cr	Fe	Ni	Mo	W	Total(Mass%)
1	28.75	3.48	7.83	37.51	0	14.4	8.03	100
2	0.12	2.9	5.82	35.51	0	31.22	24.44	100
3	0.03	2.25	6	36.14	0	32.26	23.32	100
4	10.36	1.16	5.62	72.55	0	5.76	4.56	100
5	0.18	0.62	6	84.45	0	4.8	3.96	100

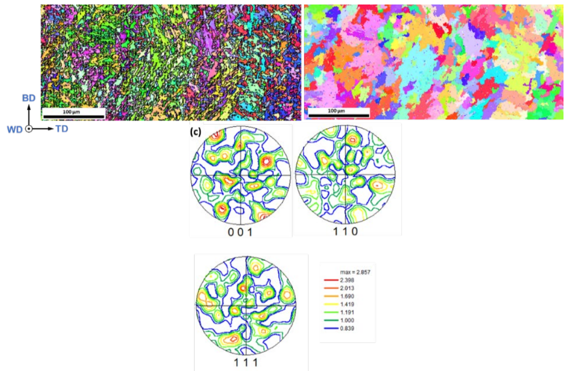
Points	Ti	V	Cr	Fe	Ni	Mo	W	Total (Mass%)
6	0.98	7.11	7.04	57.9	0	16.31	10.66	100
7	0.64	2.08	7	76.29	0	8.27	5.72	100
8	1.11	7.44	7.17	59.04	0.14	16.02	9.07	100
9	0.58	3.17	6.17	73.86	0	8.52	7.71	100
10	0.33	4.41	7.34	70.3	0	10.95	6.68	100

The chemical composition of some carbides within the martensitic structure of deposited Fe3MC1 alloy



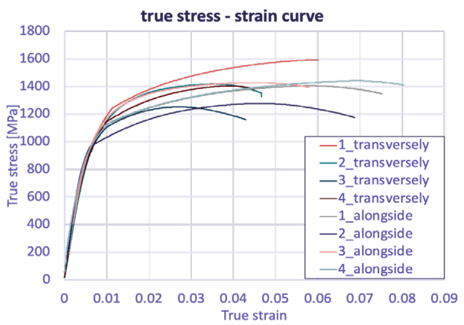




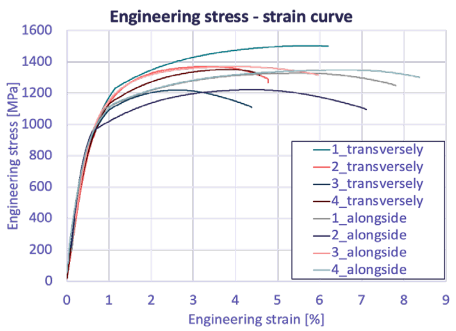


(a) : BD-IPF of martensitic structure in third deposited layer, (b) Reconstructed prior austenitic structure grains for fig. 19a, and (c) Different pole figures of martensite extracted from Fig. 19a

Some EBSD results from deposited Fe3MC1, left column: the first deposited layer and the right column is: following deposited layers (a) and (d) BD-IPF map, (b), and (e): Phase map, (c) and (f): The grain boundaries distribution map



true stress strain curves at 500 °C



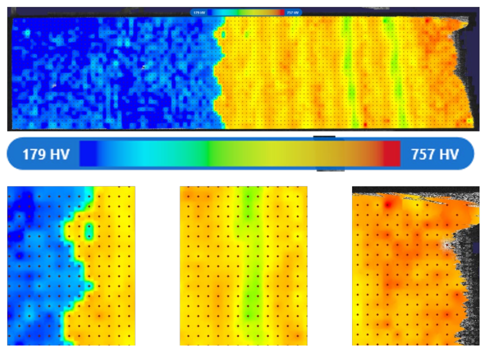
Engineering stress strain curves at 500 °C

	m_E	$R_{p0.2}$	R_m	A_t
	GPa	MPa	MPa	%
1_transversely	205,01	1108,48	1502,70	6,2
2_transversely	172,46	1038,92	1369,15	4,8
3_transversely	239,28	900,20	1219,88	4,4
4_transversely	196,14	967,87	1351,46	4,6
1_alongside	197,20	1327,67	1328,42	7,9
2_alongside	205,80	880,20	1221,55	7,1
3_alongside	----------	---------	1368,34	6,0
4_alongside	205,73	1025,52	1347,15	8,4

Youngs Modulus, Yield strength, Ultimate tensile strength and Area reduction of tensile tests at 500 °C (PWR)

layer	temperature	Hardness (HRC)	Average hardness (HRC)	comment
1	485°C	40,57 41,83 41,9	41,43	layer is not tempered
2		27,73 35,67 32,84	32,08	
3		35,10 36,61 30,70	34,13	
4		35,21 41,21 40,66	39,02	

Hardness test results of B6 coupon, AM Fe3MC1, at 485 °C



Vickers hardness (HV0.1) map at the sample surface at room temperature. Left image indicates the base plate blue (S355J2) Right side the top-layer of the coupon. (PWR)