

# Effect of laser welding parameters on the microstructure and mechanical properties of dissimilar hastelloy X/Haynes 188 joints

Joël Alexis, Jérémie Graneix, Yannick Balcaen

## ▶ To cite this version:

Joël Alexis, Jérémie Graneix, Yannick Balcaen. Effect of laser welding parameters on the microstructure and mechanical properties of dissimilar hastelloy X/Haynes 188 joints. 2024. hal-04490128

## HAL Id: hal-04490128 https://hal.science/hal-04490128

Preprint submitted on 5 Mar 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Dear Author,

Here are the proofs of your article.

- You can submit your corrections online, via e-mail or by fax.
- For **online** submission please insert your corrections in the online correction form. Always indicate the line number to which the correction refers.
- You can also insert your corrections in the proof PDF and email the annotated PDF.
- For fax submission, please ensure that your corrections are clearly legible. Use a fine black pen and write the correction in the margin, not too close to the edge of the page.
- Remember to note the **journal title**, **article number**, and **your name** when sending your response via e-mail or fax.
- **Check** the metadata sheet to make sure that the header information, especially author names and the corresponding affiliations are correctly shown.
- **Check** the questions that may have arisen during copy editing and insert your answers/ corrections.
- **Check** that the text is complete and that all figures, tables and their legends are included. Also check the accuracy of special characters, equations, and electronic supplementary material if applicable. If necessary refer to the *Edited manuscript*.
- The publication of inaccurate data such as dosages and units can have serious consequences. Please take particular care that all such details are correct.
- Please **do not** make changes that involve only matters of style. We have generally introduced forms that follow the journal's style. Substantial changes in content, e.g., new results, corrected values, title and authorship are not allowed without the approval of the responsible editor. In such a case, please contact the Editorial Office and return his/her consent together with the proof.
- If we do not receive your corrections within 48 hours, we will send you a reminder.
- Your article will be published **Online First** approximately one week after receipt of your corrected proofs. This is the **official first publication** citable with the DOI. **Further changes are, therefore, not possible.**
- The **printed version** will follow in a forthcoming issue.

## Please note

After online publication, subscribers (personal/institutional) to this journal will have access to the complete article via the DOI using the URL: http://dx.doi.org/[DOI].

If you would like to know when your article has been published online, take advantage of our free alert service. For registration and further information go to: <u>http://www.link.springer.com</u>.

Due to the electronic nature of the procedure, the manuscript and the original figures will only be returned to you on special request. When you return your corrections, please inform us if you would like to have these documents returned.

# Metadata of the article that will be visualized in OnlineFirst

ArticleTitle	Effect of Laser Weldin Hastelloy X/Haynes 18	ng Parameters on the Microstructure and Mechanical Properties of Dissimilar 88 Joints
Article Sub-Title		
Article CopyRight	The Minerals, Metals a (This will be the copyr	& Materials Society and ASM International ight line in the final PDF)
Journal Name	Metallurgical and Mate	erials Transactions A
Corresponding Author	Family Name	Alexis
	Particle	
	Given Name	Joël
	Suffix	
	Division	LGP, ENIT/INPT
	Organization	Université de Toulouse
	Address	47 av. d'Azereix, BP1629, 65016, Tarbes cedex, France
	Division	Laboratoire Génie de Production
	Organization	Ecole Nationale d'Ingénieurs de Tarbes
	Address	47 Avenue d'Azereix, BP1629, 65016, Tarbes Cedex, France
	Phone	
	Fax	
	Email	Joel.alexis@enit.fr
	URL	
	ORCID	
Author	Family Name	Graneix
	Particle	
	Given Name	Jérémie
	Suffix	
	Division	LGP, ENIT/INPT
	Organization	Université de Toulouse
	Address	47 av. d'Azereix, BP1629, 65016, Tarbes cedex, France
	Phone	
	Fax	
	Email	Jeremie.graneix@enit.fr
	URL	
	ORCID	
Author	Family Name	Balcaen
	Particle	
	Given Name	Yannick
	Suffix	
	Division	LGP, ENIT/INPT
	Organization	Université de Toulouse
	Address	47 av. d'Azereix, BP1629, 65016, Tarbes cedex, France
	Phone	

	Fax Email URL ORCID	Yannick.balcaen@enit.fr
	Received	10 May 2021
Schedule	Revised	
	Accepted	29 August 2021
Abstract	Laser welding is currently a v and propulsion units and to re autogenous laser welding seer welding of thin alloy sheets us Haynes 188 are the two base n determine the weldability don seams are investigated. EBSD the high-power welded seam, density in its fusion zone. Des were found to be satisfactory	ersatile and reliable assembly technique. To save weight in aerostructures duce thermal distortions and the heat-affected zones in these assemblies, ns promising. This experimental work addresses dissimilar autogenous laser sing a Yb:YAG source and a particular optical fibre setting. Hastelloy X and netals studied for this assembly. An experimental design allows us to nain. The macro- and microstructure and mechanical properties of the weld and EDS analysis revealed microstructural and chemical heterogeneities in but XRD results demonstrated a homogeneous depletion of the carbide pite such microstructural features, the mechanical properties of Haynes 188 and slightly greater than those of the weaker Hastelloy X.
Footnote Information	Manuscript submitted May 10	, 2021; accepted August 29, 2021.

# <sup>4</sup> Effect of Laser Welding Parameters <sup>5</sup> on the Microstructure and Mechanical Properties <sup>6</sup> of Dissimilar Hastelloy X/Haynes 188 Joints



JOËL ALEXIS, JÉRÉMIE GRANEIX, and YANNICK BALCAEN

Laser welding is currently a versatile and reliable assembly technique. To save weight in aerostructures and propulsion units and to reduce thermal distortions and the heat-affected zones in these assemblies, autogenous laser welding seems promising. This experimental work addresses dissimilar autogenous laser welding of thin alloy sheets using a Yb:YAG source and a particular optical fibre setting. Hastelloy X and Haynes 188 are the two base metals studied for this assembly. An experimental design allows us to determine the weldability domain. The macro- and microstructure and mechanical properties of the weld seams are investigated. EBSD and EDS analysis revealed microstructural and chemical heterogeneities in the high-power welded seam, but XRD results demonstrated a homogeneous depletion of the carbide density in its fusion zone. Despite such microstructural features, the mechanical properties of Haynes 188, were found to be satisfactory and slightly greater than those of the weaker Hastelloy X.

https://doi.org/10.1007/s11661-021-06452-w

© The Minerals, Metals & Materials Society and ASM International 2021

## I. INTRODUCTION

26 IN jet engines, performance and efficiency are directly 27 related to the combustion temperature. This statement 28 has promoted the constant research and development of 29 new alloys and new thermomechanical routes to produce disks, blades, combustion chambers and 30 exhausts.<sup>[1-3]</sup> Several superalloys can be associated with 31 32 optimizing the different parts of the combustion cham-33 bers depending on the mechanical and environmental constraints. The nickel-based alloy Hastelloy X is, for 34 35 example, associated with the Haynes 188 cobalt-based 36 alloy in projected engines. These alloys are commonly 37 assembled by semi-automatic gas tungsten arc welding 38 (GTAW) techniques with filler wires of the same grade as nickel-based superalloys.<sup>[4]</sup> These welding techniques 39 produce a high thermal distortion due to high energy 40 input. In contrast, the laser welding process induces 41 smaller deformations and can be automated.<sup>[5]</sup> More-42 over, new laser sources, such as disk laser sources, look 43 44 promising. Currently, disk lasers have a higher power, higher efficiency and higher optical quality than older 45  $CO_2$  laser sources.<sup>[6,7]</sup> 46

Manuscript submitted May 10, 2021; accepted August 29, 2021.

METALLURGICAL AND MATERIALS TRANSACTIONS A

The weldability of a superalloy is inversely propor-47 tional to the presence of hardening elements. An 48 acceptable level of weldability has been set at maximum 49 levels of 6 pct at. titanium and aluminium.<sup>[8]</sup> The 50 presence of these chemical elements, which determine 51 the transformations  $\gamma/\gamma'$  as well as chemical elements other than sulphur or phosphorus,<sup>[9]</sup> can cause hot 52 53 cracking by liquation or alternatively embrittlement 54 55 phenomena after ageing treatment. Liquidation-induced cracks or hot cracks appear at the joints of grains 56 enriched in the solute and are subjected to stress.<sup>[10]</sup> To 57 improve their weldability, the base metals (BMs) must in 58 particular have a small grain microstructure with no pre-weld heat treatment.<sup>[11]</sup> It is preferable to weld 59 60 annealed superalloy sheets and not after a quenching 61 and tempering treatment (final condition before use). 62 The annealed condition is more malleable and allows for 63 better accommodation of cooling-induced deformations 64 during welding. The nature of the grain boundaries also 65 seems to play a role in the weld quality. Special grain 66 boundaries significantly reduce the susceptibility to cracking.<sup>[11]</sup> Notably, there has been very little docu-67 68 mentation regarding the homogeneous Yb:YAG laser 69 welding of the superalloys Hastelloy X and Haynes 188.<sup>[12, 13]</sup> This is even more evident for the heteroge-70 71 neous welding of these two alloys. The success of 72 dissimilar welds involves the metallurgical compatibility 73 of the BMs and filler metal, similar coefficients of 74 thermal expansion and post-weld heat treatment 75 (PWHT) requirements. Researchers interested in GTAW welds, even  $CO_2$  laser welding of these two 76 77 alloys, reported some problems of liquation, segregation 78

 Journal : MMTA
 Dispatch : 6-9-2021
 Pages : 11

 PIPS No. : 6452
 LE
 TYPESET

 MS Code :
 CP
 DISK

xxx—1

1 2 3

7 8

9 10

11

12

13

14

15

16

17

18

19

20

21 22

24

25

JOËL ALEXIS, JEREMIE GRANEIX, and YANNICK BALCAEN are with the Université de Toulouse, LGP, ENIT/INPT, 47 av. d'Azereix, BP1629, 65016 Tarbes cedex, France. JOËL ALEXIS is also with the Laboratoire GVénie de Production, Ecole Nationale d'Ingénieurs de Tarbes, 47 Avenue d'Azereix, BP1629, 65016 Tarbes Cedex, France, Contact e-mail: Joel.alexis@enit.fr.

in the fusion zone (FZ) and the absence of a heat-af-fected zone (HAZ).<sup>[14]</sup> The strength of the welds is 79 80 slightly lower than that of the BM, and their ductility is 81 also weaker. Variations in mechanical properties are 82 noted according to the nature and size of the FZ substructures.<sup>[11,12]</sup> The most resistant structure seems to 83 84 be a fine dendritic structure,<sup>[13]</sup> which is obtained by 85 86 minimizing the welding energy while maximizing the 87 solidification rate.

88 It is well known that the control of welding param-89 eters plays a leading role in the welding mode (conduc-90 tion or keyhole) and the microstructure of the FZ. The 91 purpose of this paper is to highlight the effect of 92 Yb:YAG laser welding process parameters on the 93 dissimilar welding of Hastelloy X and Haynes 188 94 sheets. The weldability domain of the heterogeneous 95 assembly is presented in the first section as a function of 100 Author Proof در ۲۰۰۰ the power density and interaction time. Optimum welding conditions are determined, and the obtained weld seams are analysed. The microstructure of these seams is presented as well as their mechanical properties.

#### II. EXPERIMENTAL METHODS

#### 101 A. Materials

102 Hastelloy X nickel-based alloy and Haynes 188 103 cobalt-based alloy sheets (1.2 mm thick) were used. The plates underwent a solution annealing treatment 104105 (1150 °C for 1 hour, water quenching for Hastelloy X; 106 1475 °C, 1 h, water quenching for Haynes 188). The 107 average grain size was 90  $\mu$ m for the Hastelloy X sheet (# 4, ASTM E112 standard) and 70  $\mu$ m for the Haynes 108 109 188 sheet (# 4.5, ASTM E112 standard). The chemical 110 compositions and mechanical properties of the materials are given in Tables I and II, respectively. 111

#### 112 **B.** Laser Welding

113 The welds were performed on a TruLaser Cell 3000 114 machine, which was equipped with a TruDisk Yb:YAG 115 laser source of 3.3 kW and a coaxial optical "2 in 1" 116 fibre (100  $\mu$ m centre fibre, and 400  $\mu$ m peripheral fibre).<sup>[15]</sup> This machine has distinctive features including 117 118 the ability to dynamically vary the spot diameter at the 119 focal point as well as its position along the optical axis. 120 The Yb:YAG laser beam is generated from a disk, is 121 guided in an optical fibre and is delivered with a near 122 top-hat power density distribution at the focal point. 123 The core fibre (CF) generates a conventional near 124 Gaussian beam profile, and the outer fibre (OF) delivers 125 an annular top-hat power distribution. The use of either 126 fibre configuration provides an adjustable focal diameter 127 of 110 to 370  $\mu$ m for the CF and 450 to 750  $\mu$ m for the 128 OF. The focal diameters between 370 and 450  $\mu$ m are 129 therefore inaccessible.

To limit the number of samples while trying to 130 investigate the influence of multiple parameters of the 131 laser welding process explained above, experimental 132 133 designs were developed using CORICO software, devel-134 oped by CORYENT Company. This software provides



METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK

Table II. Mechanical Properties of the Hastelloy X and Haynes 188 Sheets

		E (GPa)	YS (MPa)	UTS (MPa)	A (Pct)	HV0.5
Hastelloy X	RD 45° TD	$208 \pm 10$ $211 \pm 15$ $100 \pm 20$	$446 \pm 3$ $446 \pm 11$ $456 \pm 5$	$799 \pm 2$ $793 \pm 11$ $806 \pm 5$	$55 \pm 2$ $53 \pm 2$ $58 \pm 8$	230 ± 10
Haynes 188	1D RD 45° TD	$190 \pm 20$ $188 \pm 1$ $200 \pm 1$ $201 \pm 1$	$436 \pm 3$ $524 \pm 10$ $516 \pm 4$ $527 \pm 8$	$806 \pm 5$ $1057 \pm 14$ $1048 \pm 3$ $1055 \pm 7$	$   58 \pm 8 $ $   76 \pm 2 $ $   71 \pm 2 $ $   72 \pm 2 $	275 ± 11

a data analysis tool that allows us to design and process
non-orthogonal experimental designs and manage nonlinear responses. CORICO software evaluates data by
the iconographic correlation method.

144 The optimal welding parameters were determined 145 using CORICO software based on "desirability" criteria 146 attributed to the geometric criteria described in the 147 standard and to the mechanical properties of the beads 148 such as yield strength and percent elongation. For each 149 response Y, a regression equation is created from the 150 iconographic correlations by CORICO software.

$$Y_I = b_0 + b_1 X_{1i} + \dots + b_P X_{Pi} + u_i$$

152 153  $b_{\rm p}$  are the coefficients of the partial regression model, 154 the constant  $u_i$  is the residue term and the regressors  $X_{pi}$ 155 are factors or logical combination of factors correlated 156 to the best answer. From the regression equations, 157 optimisation was performed using also the CORICO 158 software, implementing a Monte Carlo optimisation 159 method. The desirability criterions of this optimisation 160 process are determined on mechanical properties 161 enhancement (both static and fatigue) expected by 162 geometrical features such as a moderately wide weld 163 bead, with very low or no undercut and strictly no underfill. All this procedure is identical to previous work 164 on both alloys, as.<sup>[16]</sup> 165

166 The variable parameters of the different experimental designs are as follows: laser source power P (W), 167 welding head travel speed V (m min<sup>-1</sup>), gas flow rate 168 169 D (L min<sup>-1</sup>), geometrical configuration of the CF or OF 170 beam, and spot diameter at the focal point  $\mathcal{O}f(\mu m)$ . The 171 first three parameters are common to all welding 172 processes. The last two parameters are generally asso-173 ciated with the machine configuration. In view of the 174 results of the bibliography, other welding parameters 175 have been fixed, namely, the welding direction corre-176 sponds to the rolling direction, the position of the focal 177 point is at -1/3 of the sheet thickness, and the gas shielding towards the weld is argon (20 L min<sup>-1</sup>). Thirty 178 179 samples were welded according to the experimental 180 design given for each geometrical configuration. The 181 different weld beads were then observed from metallo-182 graphic sections to characterize their shape and size. 183 More detailed information is available in a previous 184 publication.<sup>[12]</sup>

### C. Characterization

The microstructure of the weld seams was determined 186 from metallographic cross sections obtained with the 187 188 following preparation procedure: polishing to SiC 4000 grit paper and then polishing to  $1/4 \mu m$  diamond paste 189 and etching for 2 s with 96 pct HCl and 4 pct H<sub>2</sub>O<sub>2</sub> 190 solution. Optical microscopy observations made it 191 possible to determine the weldability domain from the 192 morphologies of the weld seams and their defects. The 193 microstructure of the welds was investigated by optical 194 195 (PMG3 Olympus), scanning electron microscopy (SEM, JEOL 7000F) and electron backscatter diffraction 196 (EBSD) analyses (Oxford Nordlys Fast camera). The 197 198 precipitation density and the evolution of the lattice parameter of the solid solution  $\gamma$  were analysed by 199 electron diffraction with transmission electron micro-200 scopy (TEM, JEOL JSEM 2100F) and X-ray diffraction 201 (XRD) (line ID15 of the ESRF facility with a wave-202 length of 0.0142222 nm). The hardness was determined 203 using a ZWICK-ROELL ZHU2.5 instrumented hard-204 ness tester at a 500 g load. The tensile tests were carried 205 out using a DEBEN microtensile machine equipped 206 with a 5 kN load cell at a strain rate of  $10^{-3}$  s<sup>-1</sup> to 207 determine the mechanical behaviour of the produced 208 assemblies. 209

#### III. RESULTS AND DISCUSSION

#### A. Domain of Weldability

The weldability domains of the Hastelloy X-Haynes 212 213 188 heterogeneous welds are shown in Figure 1 as a function of the power density and interaction time. No 214 cracks in the molten zone or at the interface between 215 molten zone and the heat affected zone were observed by 216 X-ray analysis or by optical observation of metallo-217 graphic section. Almost all the welds made with the CF 218 exhibited sufficient penetration and a geometry in 219 accordance with the NF L 06 395 2000 standard, but 220 the result is different for the welds made with the OF. 221 Indeed, only a few welds have sufficient penetration and 222 223 comply with the criteria of the standard. A minimum power density of  $10^6 \text{ W cm}^{-2}$  and a fluence higher than 224 5 kJ cm<sup>-2</sup> are therefore necessary to achieve compliant 225 226 welds with the OF. The majority of compliant heterogeneous welds are common to the homogeneous welds of both alloys (Figure 2).<sup>[12, 13]</sup> 227 228

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages: 11
PIPS No. : 6452		TYPESET
MS Code :		DISK

xxx—3

185

210

211



Fig. 1—Weldability domains of the heterogeneous Hastelloy X-Haynes 188 junctions.



Fig. 2-Weldability domains of the heterogeneous Hastelloy X-Haynes 188 junctions and Hastelloy X or Haynes 188 junctions.

The welding conditions optimized to obtain sufficient penetration and bead geometry that comply with the abovementioned standard were determined using COR-ICO software from CORYENT. The optimal processing conditions are given in Table III.

255 Contaitions are given in Table III.

## 234 B. Microstructure of the Optimized Welds

235 SEM micrographic cross sections of the obtained weld 236 seams are presented in Figure 3(a) and (b). The 237 optimized heterogeneous bead obtained with the core 238 fibre has well-defined interfaces between the BM and the 239 FZ. Contrary to what was observed for the homogeneous assemblies,<sup>[12]</sup> no cracks were found on this 240 241 heterogeneous weld bead. This result can be induced by 242 the low welding speed implemented (1 mm min<sup>-1</sup>). The 243 alloys studied, particularly Hastelloy X, are susceptible to liquation-induced hot stress cracking. A low welding 244 rate leads to a decrease in cooling rate during solidification and consequently a decrease in thermal stresses.<sup>[17, 18]</sup> The filling of liquefied grain boundaries is also 247 proposed as factor contributing to the prevention or 248 reduction of hot cracking especially in laser welding of 249 Hastelloy X. 250

251 Some grain boundaries close to the melted zone are marked, particularly on the Hastelloy X side. Liquation 252 zones are observable (Figure 3(c)). These different 253 analyses also remain true for welds made with the OF. 254 The presence of cellular growth and dendritic zones was 255 determined from micrographic observations at a higher 256 magnification. Typical micrographs are shown in 257 258 Figure 3(d) to (f). The proportion of dendritic zones is 259 very important in the Hastelloy X/Haynes 188 core fibre weld seam. The cellular zone represents only a 150  $\mu$ m 260

Author Proof

METALLURGICAL AND MATERIALS TRANSACTIONS A

	Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
	PIPS No. : 6452		TYPESET
-	MS Code :		DISK

261 thick border at the BM-FZ interface. This result is not 262 the same for the Hastelloy X/Haynes 188 weld obtained 263 by the OF since the proportions of dendritic and cellular 264 zones tend to be equal. This last weld is formed of a 265 broad cellular area close to the BM and a dendritic zone 266 in its centre.

267 SEM backscattered electron observations revealed 268 chemical contrasts in the FZ (Figure 4(a), (b)), con-269 firmed by energy dispersive spectroscopy (EDS) analy-270 ses. The chemical composition of the CF bead FZ 271 appears to be relatively homogeneous at a macroscopic 272 scale (Figure 4(d), (f)). EDS profiles confirm this 273 statement in the centre of the cords. Only slight 274 variations (approximately 2 to 3 pct) are detected over 275 100  $\mu$ m distances. On the other hand, significant 276 macrosegregations are observed in the Hastelloy X/ 277 Hayne 188–OF cords (Figure 4(c) and (e)). Some areas 278 of the melted zone present high concentrations of nickel 279 and molybdenum, a major alloying element of Hastelloy 280 X, and other areas are cobalt and tungsten rich,

Table III. Processing Parameter Values for Optimized Welds According to Criteria Based on the Standard NF L 06 395 2000

	Core Fibre	Outer Fibre
Power (W)	765	2330
Welding Speed (m min $^{-1}$ )	1	4.62
Spot Size (µm)	203	527
Face Argon Flow $(1 \text{ min}^{-1})$	35	40
Power Density (kW $cm^{-2}$ )	2363	1277
Fluence (kJ cm <sup>-2</sup> )	28.8	8.7

typically originating from Haynes 188. These global 281 analyses were supplemented by local analyses, which 282 showed a slight increase in the chromium, molybdenum 283 and tungsten contents in the interdendritic zones. 284

285 The evolution of the ratio of the thermal gradient to 286 the solidification rate (G/R) explains the microstructural changes in the fusion zone. The microstructure of the 287 weld can progressively change from a planar solidifica-288 tion mode at the interface of the weld (maximum G/R), 289 to a cellular mode and then to a dendritic mode in the 290 291 central region of the FZ due to the decrease of G/R292 towards the centerline of the FZ. On one hand, the 293 CF-obtained seam presents an homogeneous distribution of chemical species, and a dendritic structure. This 294 could indicate a moderate solidification time and an 295 296 enhanced expression of constitutional supercooling. On the other hand, the weld seam obtained with OF, high 297 298 power setting and quite high welding speed, presents a 299 heterogeneous distribution of solute (Figure 4(e)). The 300 discontinuous nature of metal-weld solidification produces the formation of solute bands within the weld. 301 The growth rate fluctuates cyclically above and below a 302 303 mean value which is a function of the welding speed. Correlated to the presence of a thicker cellular zone, 304 305 exposed at Figure 3(b), it could be related to a higher 306 solidification rate, and steeper thermal gradient, limiting the abovementioned phenomenon. 307

The microstructures observed for the heterogeneous 308 bead obtained with the CF are very similar to those of 309 the homogeneous cords (Figure 5).<sup>[10]</sup> The solidification 310 of the FZ begins with epitaxial growth from partially 311 melted grains. This zone obeys a cellular growth mode. 312 Then, the growth of some favourably oriented grains, 313 presenting (100) to the joint plane, appears. The welding 314



Fig. 3—Cross-sectional observations of the optimized weld by scanning electron microscopy. (a, b) Overall observation and (c, d) observation of the fusion zone–Hastelloy X interface.

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK



**Joold Tolling** Core Fig. 4–

Fig. 4—EDS mappings made in the TD-ND plane of the heterogeneous assemblies of Hastelloy X/Haynes 188. Optimized welds obtained by (a, c, e) outer fibre and (b, d, f) core fibre..



Fig. 5—IPF  $Z_0$  coded EBSD cartographies of the optimized welded seams of the heterogeneous Hastelloy X/Haynes 188 assemblies, on the cross sections (top) and longitudinal sections 400  $\mu$ m above the median plane of the sheet (bottom).

315 speed seems sufficiently important to extend the melt 316 pool backwards; the grains then develop in the direction 317 of the higher temperature gradient. The OF weld 318 microstructures are significantly different. A columnar 319 zone consisting of epitaxially grown grains remains. 320 However, the width of this area is very limited. On the 321 other hand, large odd-shaped grains are observed in the 322 centre of the weld. The joint plane is then more diffuse in 323 this cord. Comparing data displayed on Figures 3(b) 324 and 4(c) and 5 top right, it seems that odd-shaped grains

325 appearance is correlated to dendritic microstructure in poorly-mixed solute areas. These microstructural evo-326 lutions have not been demonstrated in homogeneous 327 seams, even if some optimized homogenous assemblies 328 329 have been developed with very close processing parameters. The possible explanation of this particular 330 microstructure could be related to the poor mixing of 331 the chemical species in the weld pool, leading to steep 332 chemical gradients in it, promoting such heterogeneous 333 nucleation. 334

#### METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK



Fig. 6—MET observations of the precipitates present in the weld bead obtained with the (a to c) CF and (d to f) OF. The (c) sigma phase precipitate and (f)  $M_6C$  carbide. Indexing of the diffraction patterns with Carine software.

335 The shape and size of the particles in FZs are highly 336 variable (Figure 6(a) to (f)). In addition, these particles 337 differ from those observed in the two reference alloys. 338 Their shape in FZs can be characterized as tortuous and 339 very rounded. The particles whose sizes were less than 340 500 nm in the Haynes 188 alloy had an angular shape, 341 and the larger particles were rounded. For the Hastelloy 342 X alloy, particles below 500 nm were rounded. The 343 structure of some particles was determined by diffrac-344 tion. The selected area diffraction pattern of the oriented 345 particles, presented in Figure 6(c), can be indexed 346 according to the [001] zone axis of the tetragonal  $\sigma$ 347 phase (P42/mnm space group, lattice parameters a =348 0.91 nm and c = 0.48 nm). Figure 6(f) shows the pattern 349 obtained for one of the observed carbides. The 0.40 nm 350 inter-reticular distance corresponds to the (220) planes 351 of the face-centred cubic (FCC) M<sub>6</sub>C carbide. To 352 confirm the nature of the M<sub>6</sub>C carbides, several zone 353 axis were analysed on some particles (Figure 7).

354 In the melted zone of the OF seams, EDS analysis 355 highlighted two typical particles: carbides, identified as 356  $M_6C$ , and lanthanum-rich particles (Table IV). The 357 M<sub>6</sub>C particles generally surround the lanthanum-rich 358 particles (Figure 6(f)). Regarding the particles in the FZ 359 of the CF, three typical compositions are highlighted: 360  $\sigma$ -phase particles, M<sub>6</sub>C carbides and lanthanum-rich 361 particles. The chemical composition of the M<sub>6</sub>C carbides 362 present in the molten zone whatever the fiber used (CF 363 or OF) is different from that of the carbides analyzed in 364 each alloy. They contain both Molybdenum and Tung-365 sten. In addition, lanthanum-rich particles are not 366 detected in the base alloys. The precipitation of these 367 second phases (M<sub>6</sub>C,  $\sigma$ ) in the interdendritic zones have

already been observed by many authors.<sup>[19, 20]</sup> A. 368 Ghasemi et al. show that the M<sub>6</sub>C and  $\sigma$  phases appear 369 at the end of solidification of Hastelloy X alloy between 370 1315 and 1280 °C due to the segregation of chromium 371 and molybdenum and not during a solid state transformation during cooling.<sup>[21]</sup> 373

The evolution of the precipitate densities in the FZ 374 was determined via X-ray analysis by the evolution of 375 376 the  $M_6C$  (422) peak intensity in the FZ compared to the 377 same peak in the BM (Figure 8). The X-ray probe spot 378 was assimilated to a 100  $\mu$ m diameter disk, scanning the 379 total width of the seam from the BM to BM through the sheet thickness. Superimposing the geometry of the 380 cords on these data, the intensity ratio does not change 381 identically with respect to the two CF and OF cords 382 (Figure 9). With the CF, the population of  $M_6C$ 383 precipitates decreases progressively from the BM to 384 the centre of the FZ. Therefore, there appears to be a 385 precipitate density gradient within the FZ. The width of 386 the zone containing a very small proportion of M<sub>6</sub>C 387 carbide in the centre of the FZ for the CF condition 388 corresponds approximatively to the width of the laser 389 beam for a power density greater than  $10^6 \text{ W cm}^{-2}$ . The 390 dissolution seems more important in this area. For OF 391 welding, this progressive evolution disappears, and the 392 peak relative intensity remains constant in the FZ at the 393 20 pct level. These results are comparable to those of the 394 Haynes 188 homogeneous assemblies.<sup>[12]</sup> 395

The lattice parameter of the solid solution in the FZ is 396 different from that of the nickel-rich solid solution 397 (Hastelloy X) or cobalt-rich solid solution (Haynes 188) 398 (Figure 10). At the centre of the welds, an intermediate 399

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK



Fig. 7-Electron diffraction patterns of an M<sub>6</sub>C carbide for four different zone axis orientations [011] [111] [112] and [132].

Table IV.	Chemical	Composition of	Particles	Observed	in Alloys	and	Welds
-----------	----------	----------------	-----------	----------	-----------	-----	-------

Atomic Percent	Cr	Ni	Co	Fe	Mo	W	La
M <sub>6</sub> C Carbide (Hastelloy X Alloy)	27	26	7_	10	35-37	1	
M <sub>6</sub> C Carbide (Haynes Alloy)	27-28	11-15	23-28	1	0.5-1	29-33	
M <sub>6</sub> C Carbide (OF Weld)	35-40	17-23	10-19	6-8	10-18	5	
M <sub>6</sub> C Carbide (CF Weld)	43	16	16	7	18	6	
$\sigma$ Phase (CF Weld)	33	29	15	9.5	9	4	
Lanthanum-Rich Precipitates (OF and CF Welds)	6–18	4–23	3–10	1–7	2–5	0-1	36-83



Fig. 8—Superimposed X-rays diffractograms obtained through weld seam.

8—xxx

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK



Fig. 9—Location of the X-ray diffraction analysis of the Hastelloy X–Haynes 188 welds obtained in the CF and OF (top). Diffraction intensity ratio by the (422) planes of the  $M_6C$  precipitates in the weld with respect to the base metal.



Fig. 10-Evolution of the FCC solid solution lattice parameter..

400 value is taken because of the interdiffusion phenomena401 between Ni and Co in the bead.

#### 402 C. Mechanical Properties of the Optimized Welds

403 The mechanical behaviour of the welded specimens is 404 explored through tensile tests, and the results are 405 presented in (Figure 11). The tensile behaviour is 406 intermediate between the two BMs. The mechanical 407 strength of the welded specimens, regardless of the 408 selected fibre, is actually close to that of the Hastelloy X 409 alloy (Table V). A slight reduction in the ductility is 410 recorded for the CF welds compared to the OF welds. 411 The fractures of all the specimens are localized in the Hastelloy X BM, several millimetres from the FZ. This 412 finding explains the values of the mechanical properties 413 of the heterogeneous weld seams solicited in transverse 414 directions. The mechanical strength of these welded 415 specimens is in fact conditioned by the maximum 416 strength of the weaker Hastellov X. The slight difference 417 in the ductility recorded is explained by a purely 418 geometric effect (different width of the welds depending 419 on the type of fibre compared to the length of the useful 420 421 zone). The mechanical properties of the welds (FZ and HAZ) were determined using tensile specimens extracted 422 in the FZ along the welding direction (Figure 9). The 423 results obtained for the welds confirm the first results in 424 the transverse direction. The mechanical properties of 425

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
PIPS No. : 6452		TYPESET
MS Code :		DISK

Author Proof



Fig. 11—Tensile tests performed on heterogeneous and homogeneous welds in the transverse direction (a) and welding direction (b)...

Table V. Mechanical Properties of Heterogeneous Assemblies Hastelloy X/Haynes 188 (Tensile Tests in the Transverse Direction)

Test Direction		UTS (MPa)	Elongation (Pct)	Fracture Localization
	Hastelloy X Haynes 188	$795 \pm 8$ $974 \pm 36$	$48 \pm 0.1 \\ 57 \pm 1.7$	
Transverse Welding Direction Transverse Welding Direction	core fibre outer fibre	$819 \pm 2 \\ 807 \pm 2$	$29 \pm 0.6 \\ 33 \pm 0.3$	Hastelloy X BM Hastelloy X BM
Welding Direction Welding Direction	core fibre outer fibre	$792 \pm 4$ 767 $\pm 13$	$29 \pm 1.6$ $25 \pm 1.6$	

429

426 the fused zone solicited in the welding direction for the

- Hastellov X/Havnes 188 heterogeneous welds are close 427
- to those of the Hastellov X welds (Table V). 428

#### **IV. CONCLUSION**

430 Two different optima were determined for each type 431 of fibre, essentially based on geometrical defect reduc-432 tion. Both optimums produce power densities above  $10^6$ 433 W.cm<sup>2</sup> but very different fluence levels, leading to a 434 counter-intuitive wider FZ for the CF weld seam than for the OF weld seam. The obtained weld seams are 435 sound, with weak liquations. The microstructure of the 436 437 FZ consists of a fine cellular growth zone, which evolves dendritically in the centre of the FZ. The width of the 438 439 cellular zone is more important in the selected OF 440 welding condition due to the high welding speed and low 441 fluence levels, leading to a high solidification factor G/R. This high solidification rate is also confirmed by the 442 443 poor solute mixing evidenced by EDX analysis of the 444 OF weld seam. This behaviour could be the origin of the 445 odd-shaped dendritic grains in the centre of the FZ, 446 highlighted in EBSD analysis. Secondary phases, such as 447 carbides, were found to be strongly and homogeneously diluted in this seam, contrary to the CF weld seam, in 448 449 which the carbide density diminished progressively from 450 the BM to the centre of the FZ. However, the mechanical properties remain satisfactory, and fractures occur 451 452 in the weaker Hastelloy X.

#### ACKNOWLEDGMENTS

454

465

474

475

4<u>76</u>

455 The authors are thankful to EXAMECA for their 456 financial support, in particular for providing the Haynes 188 and Hastelloy X alloys. Furthermore, we wish 457 to thank Cédric Bellot, Director of ACRDM, for giv-458 ing our team access to the ACRDM synchrotron facil-459 ities at ESRF and Marie-Christine Laffont, 460 CIRIMAT, for TEM observations. 461

#### CONFLICT OF INTEREST 462

On behalf of all authors, the corresponding author 463 states that there is no conflict of interest. 464

REFERENCES	
------------	--

- 466 1. N. Rao: Advances in Gas Turbine Technology, InTechOpen, 467 2011, 13. 468
- T.M. Pollock: Nat. Mater., 2016, vol. 15, pp. 809-815.
- 469 3. A. Devaux, E. Georges, and P. Héritier: Adv. Mater. Res., 2011, 470vol. 278, pp. 405-410.
- 471 M. Sathishkumar and M. Manikandan: J. Mater. Eng. Perform., 472 2020, vol. 29, pp. 5395-5408. 473
- 5. F. Zapirain, F. Zubiri, F. Garciandía, I. Tolosa, S. Chueca, and A. Goiria: Phys. Procedia, 2011, vol. 12, pp. 105-112.
- 6. A. Giesen and J. Speiser: IEEE J. Sel. Top. Quantum Electron., 2007, vol. 13, pp. 598-609.
- 477G. Verhaeghe and B. Dance: International Congress on Applica-7 478 tions of Lasers & Electro-Optics, Temecula, California, USA, 479 Laser Institute of America, 2008, p. 710.

METALLURGICAL AND MATERIALS TRANSACTIONS A

10 - xxx

453

S	Journal : MMTA	Dispatch : 6-9-2021	Pages : 11
	PIPS No. : 6452		□ TYPESET
	MS Code :		DISK

- 480 8. ASM International, ed., ASM handbook, 10th editon, ASM International, Materials Park, Ohio, 1990.
- 482
  483
  9. J.N. DuPont, J.C. Lippold, S.D. Kiser: Welding Metallurgy and Weldability of Nickel-base Alloys, (n.d.) 456.
- 484 10. P. von Witzendorff, S. Kaierle, O. Suttmann, and L. Overmeyer:
   485 *Metall. Mater. Trans. A*, 2015, vol. 46A, pp. 1678–1688.
- 486 11. E.M. Lehockey, G. Palumbo, and P. Lin: *Metall. Mater. Trans. A*, 487 1998, vol. 29A, pp. 3069–3079.
- 488 12. J. Graneix, J.-D. Beguin, J. Alexis, and T. Masri: *Metall. Mater.* 489 *Trans. B*, 2017, vol. 48B, pp. 2007–2016.
- 490 13. J. Graneix, J.D. Beguin, J. Alexis, and T. Masri: *Adv. Mater. Res.*,
   491 2015, vol. 1099, pp. 61–70.
- 492 14. J. Hofweber, N.F. Fiore, and W.T. Ebihara: *Mater. Sci. Eng.*,
   493 1977, vol. 27, pp. 157–162.
- 494 15. W. Andreasch, R. Huber, and D. Mock: *Laser Tech. J.*, 2011, vol. 8, pp. 38–41.

 J. Graneix, J.-D. Beguin, F. Pardheillan, J. Alexis, and T. Masri: *MATEC Web Conf.*, 2014, vol. 14, p. 13006.
 J.J. Pepe and W.F. Savage: *Weld. J.*, 1970, vol. 49 (12),

496

497

498

499

500

501

502 503

504

505

506

507

508

509

510

511

- 17. J.J. Pepe and W.F. Savage: *Weld. J.*, 1970, vol. 49 (12), pp. 545s–553s.
- M. Pakniat, F. Malek Ghaini, and M.J. Torkamany: *Mater. Des.*, 2016, vol. 106, pp. 177–183.
- R. Sihotang, P. Sung-Sang, and B. Eung-Ryul: *Mater. Res. Innov.*, 2014, vol. 18 (sup2), pp. S2-1074–S2-1080.
- J. Lippold, J. Sowards, G. Murray, B. Alexandrov, and A. Ramirez: *Hot Cracking Phenomena in Welds II*, Springer, New York, 2008, pp. 147–170.
- 21. A. Ghasemi, A. Mohammad Kolagar, and M. Pouranvari: *Mater. Sci. Eng. A*, 2020, vol. 793, p. 139861.

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author Proof

METALLURGICAL AND MATERIALS TRANSACTIONS A

Journal : MMTA	Dis
PIPS No. : 6452	
MS Code :	

ATMN	Dispatch : 6-9-2021	Pages : <b>11</b>
: 6452		TYPESET
):		DISK