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imposed by the laser spot diameter are a reliable method to control

the melting ratio and maintaining the expected resistance length at the material interface. The weld configuration parameters were correlated by means of the analysis of variance (ANOVA) method with shear resistance length and the melting ratio: the incidence of surface cracks can be significantly reduced increasing the ferritic steel area, involved in the formation of seam, over 60 % of the whole melt zone. Push-out tests performed on the specimens revealed that such a configuration has beneficial aspects on the ultimate shear strength of the seam meaning that the prevailing effect is the decreased brittleness of the weld by decreasing its carbon content under 0.5 % in weight.

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The influence of laser welding configuration on the properties of dissimilar stainless steel welds

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Abstract Laser beam welding of dissimilar ferritic/ 10martensitic stainless steels was performed in constrained butt 11 12joint configuration with the objective of identifying the influ-13ence of the melting ratio between the two base metals on the 14ultimate shear strength of the welds. Based on a full factorial design, experiments demonstrated that varying the incidence 15angle up to 45° and offsetting the focal position with respect to 1617the materials' interface within the limits imposed by the laser spot diameter are a reliable method to control the melting ratio 1819 and maintaining the expected resistance length at the material 20interface. The weld configuration parameters were correlated 21by means of the analysis of variance (ANOVA) method with shear resistance length and the melting ratio: the incidence of 2223surface cracks can be significantly reduced increasing the fer-24ritic steel area, involved in the formation of seam, over 60 % of the whole melt zone. Push-out tests performed on the spec-25imens revealed that such a configuration has beneficial aspects 26on the ultimate shear strength of the seam meaning that the 2728prevailing effect is the decreased brittleness of the weld by decreasing its carbon content under 0.5 % in weight. 29

30 Keywords Laser welding · Dissimilar steels · Melting ratio

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1 Introduction

The recent advancement in manufacturing technology is in-32 creasing the demand for dissimilar metal welding. Joints be-33 tween components of different material or compositions are 34 commonly used in the power generation, chemical, petro-35chemical, nuclear, automobiles, and electronics industries 36 [1]. The ability to use different metals and compositions in a 37 product provides the designer and production engineer with 38 greater flexibility and often results in technical and economic 39 advantages over components manufactured from a single ma-40 terial. Many problems are also associated to the topic of dis-41 similar welding, depending on the metals being joined and the 42process employed. In the welding of dissimilar metals, the 43different chemical, metallurgical, and physical properties such 44 as thermal conductivity, thermal expansion coefficient, and 45melting point should be taken into consideration [2]. The for-46mation of detrimental metallurgical phases in these welds 47 could result in decrease in mechanical and functional proper-48 ties of the joint. The difference between the physical proper-49ties of the two metals to be welded leads to an asymmetry in 50heat and fluid flow which in turn directs to the development of 51unique features in the weld microstructure [3]. Thus, solidifi-52cation microstructures, the asymmetric shape of the weld, and 53mixing patterns need special attention. Among the available 54welding techniques, laser welding (high specific power and 55low-energy input process) is emerging as a valid and promis-56ing alternative for joining of dissimilar metal, as it provides 57solutions to a number of problems encountered with conven-58tional techniques [4]. 59

Laser welding provides several advantages, such as higher 60 productivity, better weld quality with narrow heat-affected 61 zone (HAZ), lower distortions, and higher flexibility over 62 the conventional processes [5]. The weld quality mainly depends on the mechanical properties, weld bead geometry, and 64

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Fig. 1 a Draft of a typical axial section of the welded components with relative dimensions. **b** Top SEM view of a dissimilar butt welded surface at the intersection of AISI 430F and AISI 440C: *x*-axis is circular and set at the material interface, and *y*-axis is positive in the direction of AISI

430F. **c** Theoretical weld bead profile and its geometrical features ($W_{\rm M}$: martensitic weld width, $W_{\rm F}$: ferritic weld width, S: resistance length) together with the areas of both material intersected by the weld ($A_{\rm M}$: supposed martensitic weld area, $A_{\rm F}$: supposed ferritic weld area)

distortion of the welded joint. All of these quality characteristics are directly related to welding parameters. Several efforts
have been done to understand the mechanical and microstructural behavior of dissimilar metal welds and to optimize the
welding processes used.

70Phanikumar et al. [3] investigated the continuous welding 71of iron and copper using a laser heat source. The microstruc-72tural analysis at different process conditions of the weld/basemetal interface shows features that are different on the two 7374 sides of the weld. Vaidya et al. [6] used Nd:YAG laser for dissimilar butt welding of aluminum AA6056 and titanium 75Ti6Al4V alloy without using a filling wire. In their study, the 7677interfacial area was decreased that resulted in decreased reaction zone, improved interfacial binding, reduced the grain size 78in the fusion zone, no segregation of grain boundary, and 7980 refined microstructure with improved properties. Homogeneous microstructure of the weld metal and very few weld 81 defects were observed in butt welding of two different thick-82 83 ness stainless steel plates [7].

Caiazzo et al. [8] studied the autogenous disk laser welding
 of dissimilar metals commonly used in aerospace applications.
 They provided a comprehensive description of the quality

t1.1 **Table 1** Average chemical composition of AISI 440C and AISI 430F steels

t1.2		%C	%Mn	%Si	%Cr	%S	%Mc
t1.3	AISI 440C	0.95-1.2	1.00	1.00	16.0–18.0	Max 0.03	0.6
t1.4	AISI 430F	0.12	1.25	1.00	16.0–18.0	Min 0.15	0.75

issues in terms of both structure and shape defects, via nonde-87 structive tests and dimensional checks by optimizing three 88 factor experimental plans with power, welding speed, and 89 beam angle. Gao et al. [9] developed the laser keyhole 90 welding of titanium and magnesium alloys and showed that 91the offset, i.e., the change of incident laser beam position, 92plays the significant role on joint properties by the change of 93 the power density irradiated at the Ti-Mg initial interface. 94 However, the variation of the beam position was not found 95 to be a less significant factor for the weld geometry in keyhole 96 mode of dissimilar austenitic-martensitic stainless steel [10]. 97

The attention paid by researchers on the weld geometry 98 testifies its influence on the mechanical properties of the 99 welded joints and, consequently, on the related welding 100quality. Liao et al. [11] studied the effects of pulse energy 101 and incident angle on the cross-sectional size and shape of 102the welded bead. Their study illustrated that laser inci-103dence angle along with the laser energy is an important 104parameter for controlling the geometry of the welded spot. 105

Weld material, joint configuration, and welding pa-106rameters have significant effects on the weld seam char-107acteristics, on the weld microstructure, on the presence 108 of defects, and on the effective mechanical properties of 109the whole joint. To optimize the welding parameters and 110to obtain proper welding geometry, various methods of 111 obtaining the desired output variables throughout model 112development can be used. Among these, design of ex-113periment (DOE) may be the most efficient way for a 114 systematic study as it grown rapidly by its diversified 115application in different areas of manufacturing. 116Benyounis and Olabi [12] reported a literature review 117

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Fig. 2 a Photographic view of Nd:YAG laser welding system. b Cross section of the joined components: welding configuration varies from the reference position (beam axis orthogonal to the surface, pointing the intersection of AISI 430F and AISI 440C) with the use of input parameters



on various optimization methods; those are applied to 118 119define the desired output variables through developing mathematical models. Anawa and Olabi [13] showed 120that ferritic/austenitic welded joints have better mechan-121 ical properties compared to base metals by the minimi-122123zation of laser power and maximization of welding speed by the application of the Taguchi approach. 124125Ruggiero et al. [14] optimized the weld bead geometry and investigated the effect of laser power, welding 126speed, and focal point position on the operating cost 127using response surface methodology (RSM). Khan 128129et al. [15] also used RSM to optimize the welding pa-130rameters (welding speed, laser power, laser incidence angle, and defocus distance) in ferritic/austenitic stain-131132less steel to obtain the most desirable weld quality in terms of weld bead geometry under predefined mechan-133134ical strength requirements.

135The laser welding mode (conduction or keyhole) affects the 136size of the fusion zone, as the dilution between two base metals strongly depends on the laser energy supply to the 137

materials. Marashi et al. [16] showed that the failure behavior 138of the fusion zone of dissimilar stainless steel is controlled by 139the dilution between two base metals. Dissimilar welding of 140low carbon to austenitic stainless steel sheets resulted in asym-141metric shape of the fusion zone as different materials having 142different thermal conductivities [17]. 143

From the above literature, it is clear that laser welding is a 144suitable technique for joining dissimilar metals and explains 145the reasons of its increasing use also in the field of thin-walled 146pressure vessels for biomedical and automotive applications 147[18]. Indeed, high-strength metal cylinders can be capped with 148a dissimilar metal of various shapes to increase the corrosion 149properties of the component (e.g., in surgery devices) or to 150enhance the wear resistance (e.g., parts of valves for precision 151mechanics), etc. 152

The extremely precise and intense energy concentration 153obtainable by modern fiber sources allows for numerous weld 154configurations at the metal interface. Among all, butt welding 155is the one which enables an easier control of the mixing be-156tween the two dissimilar steels in the melt pool [19]. 157

t2.1 t2.2	Table 2 Technical specification of the laser welding process	Laser source	Fiber laser
t2.3		Laser power (W)	800
t2.4		Fiber diameter (mm)	0.4
t2.5		Collimating (mm)	200
t2.6		Focusing (mm)	200
t2.7		Welding speed (mm/s)	65
t2.8		Shielding gas type	Argon
t2.9		Shielding gas flow rate (l/min)	6

Table 3	Experimental	conditions and response factors	t3.1
Process fa	actors	Tested values	t3.2

Process factors	Tested values			
O offset (µm)	0	100	200	
A incidence angle (°)	0	15	30	45
Constant factors				
Base material	Outer shell	AISI 4	30F	45
	Inner shell	AISI 4	40C	
Response factors				
Weld bead characteristics	Resistance ler	ngth (S)		
	Melting ratio	(MR)		

t4.1 **Table 4** Design matrix with actual factors and measured mean responses

	Standard order	Process fac	etors	Response fac	tors
		<i>O</i> (μm)	A (deg)	MR (a.u.)	<i>S</i> (μm)
	1	0	0	0.8	760
	2	100	0	2.0	695
	3	200	0	2.7	465
	4	0	15	0.5	535
	5	100	15	1.6	610
	6	200	15	2.2	450
)	7	0	30	0.3	480
L	8	100	30	0.6	550
2	9	200	30	1.5	590
	10	0	45	0.1	280
	11	100	45	0.3	415
	12	200	45	0.6	455

158Main purpose of the present research is, in fact, to go be-159yond the already studied influence of process parameters on the weld bead and, then, to identify a reproducible setup for a 160common laser welding cell to control the melting ratio be-161tween two parent metals. The effects of welding parameters 162163like laser beam position (with respect to the materials' inter-164 face) and incidence angle (with respect to the materials' irradiated surface) on the weld profile will be studied by means of 165166a structured DOEs. An attempt based on full factorial design will be proposed to mathematically link the parameters deter-167mining the butt welding configuration with the geometry of 168the melt pool and the melting ratio of two dissimilar metals. 169170This step is retained a technical key factor to determine how 171mixing two different materials could enhance the mechanical 172properties of the single base metals in butt-welded joints. At 173this purpose, the final objective is to perform disassembly tests on the obtained joints in order to detect the influence of melt-174175ing ratio on the ultimate shear strength of the welds.

2 Materials and experimental procedures

Whater hais and experimental procedures

2.1 Materials and weld design

Experiments are performed in butt constrained circular seam 178 to replicate the weld configuration of a pressure vessel. The 179draft in Fig. 1a shows the welding configuration together with 180 the specimens' diameters and their coupling. The internal tu-181 bular shell is made of martensitic stainless steel AISI 440C 182(prehardened and tempered) and is assembled with the exter-183nal one made of ferritic stainless steel AISI 430F (cold drawn, 184annealed, and centerless ground). The selected materials are 185frequently used both in automotive and biomedical applica-186tions according to peculiar design criteria which impose high 187 hardness and good resistance to corrosion as well. Table 1 188 reports the chemical composition of the used steels. 189

The inside diameter of the outer shell and the outside diameter of the seat are machined to $\emptyset7.500\pm0.025$ mm and 191 $\emptyset7.458\pm0.015$ mm, respectively, to have a clearance fit between them when the shells are assembled. 193

The geometrical features characterizing the weld seam pro-194file are defined in Fig. 1: $W_{\rm M}$ represents the weld width on the 195martensitic material while $W_{\rm F}$ represents the one on the ferritic 196 stainless steel. The ultimate shear strength of the weld is guar-197anteed by the length of the melt pool at the material interface, 198here defined as resistance length S, since the joint is supposed 199to fail under the action of disassembly forces parallel to the 200shells' axis. 201

In order to consider only the influence of the welding con-202figuration on the melt pool geometry and its composition (be-203tween the dissimilar steels), the weld seams obtained in this 204study are performed with the following laser parameters: laser 205power of 800 W, welding speed of 65 mm/s, and spot diameter 206of 0.4 mm. This combination results in an energy density (ED 207calculated as the ratio between the input power and the prod-208uct of welding speed and spot diameter) supply to the speci-209men of about 30 J/mm². Nevertheless, the findings of this 210research can be also applied to different combinations of laser 211





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Fig. 4 a View of the experimental setup for the pushout test of the weld. b Crosssectional draft of the specimen



parameters under the condition that the heat transfer is conduction dominated (up to 50–60 J/mm² according to [20]).
Heat exchanges established under the formation of a plasma
channel (as in keyhole welding mode) produce much higher
thermal transients, thus generating a remarkably different microstructure of the weld with respect to those observable when
the weld is conduction dominated.

However, even using low values of ED supply on the steels, the experimental practice often reports the occurrence of microcracks on the seam. These defects are supposed to grow up during the solidification process in zones where the mixing of the two metals with

t5.1 **Table 5** Occurrence of surface microcracks on the weld seam with respect to the analyzed weld geometries

t5.2	Welding configuration	Offset, O (μm)	Incidence angle, A (°)	Surface cracks ^a
t5.3	1	0	0	1
t5.4	2	100	0	0
t5.5	3	200	0	0
t5.6	4	0	15	3
t5.7	5	100	15	0
t5.8	6	200	15	0
t5.9	7	0	30	3
t5.10	8	100	30	2
t5.11	9	200	30	0
t5.12	10	0	45	3
t5.13	11	100	45	3
t5.14	12	200	45	2

Values are attributed according to ISO 13919-1:1996 [17], after inspection on the three samples for each configuration

^a0=no defects, 1=exist but acceptable, 2-3=not acceptable

different chemical composition and thermal properties 224 is less homogeneous. Microcracks can be classified according to the ISO 13919-1:1996 [21] standard. 226

To reduce the incidence of crack formation, which testifies 227 the embrittlement of the weld seam and mostly develops on 228 the side of the martensitic steel, it is here hypothesized to 229 change the position of the laser beam toward the ferritic steel, 230 by offsetting the beam axis with respect to the interface of the 231 two materials. 232

Nevertheless, increasing the beam offset O (along y-axis in 233Figs. 1b and 2b) may result in a drastic decrease of the resis-234tance length (up to the value for which the melt pool does not 235involve the martensitic steel) with a consequent decay in the 236ultimate shear strength. To avoid this severe limitation and, at 237the same time, to obtain a weld profile less prone to cracking, 238the beam incidence angle A (see Fig. 2b) has to be varied as 239well. This results in the need of defining weld cross-sectional 240geometries for each combination (O; A) adopted. 241

Inclining the laser beam has a further beneficial effect of 242 increasing the irradiated area which becomes elliptical (increasing A) with the longer axis disposed along y-direction. 244 The elongation of the irradiated area allows for a reduction of 245 the thermal gradient in y-direction which may contribute to a 246 less severe thermal cycle on the extinction zones of the weld 247 bead, where microcracks usually appear. 248

For each combination of (O; A), the melting ratio between 249 the two dissimilar steels is supposed to vary, thus influencing 250 the microstructural properties of the weld bead and the occurrence of surface cracking, as also stated in [22]. The melting 252 ratio can be defined by analyzing the cross section of the 253 welds as the ratio between the areas of ferrite and martensite 254 involved in the melt pool, as shown in Eq. (1): 255

$$MR = \frac{A_F}{A_M}$$
(1)

279

Fig. 5 Measurement of **a** ferritic width and **b** martensitic width for different offset positions and different incident angles. The *dashed lines* are guide to show the trend



where MR is the melting ratio, $A_{\rm F}$ is the area of ferrite, and $A_{\rm M}$ is the area of martensite. In the perspective of reducing the incidence of crack formation up to a less dangerous value for the strength of the weld, a more favorable configuration provides larger ferritic area, resulting in higher melting ratio.

This calculation implies the hypothesis of a homoge-262 neous mixing of the two dissimilar steels in the melt 263pool. As a matter of fact, the melting process is associ-264ated with the formation of convective flows [23] (espe-265cially Marangoni flows). In case of weld of different 266steels, this induces a chemical composition homogeniza-267tion of the melting pool volume. Obviously, some 268269 nonhomogeneity could be present, especially in the regions close to the HAZ, but their effects on weld prop-270erties are proportional to their extensions, thus almost 271272negligible with respect to the melting pool volume.

Positioning the focal point at the material interface, 273 avoiding any possible misalignment, is extremely important 274 for the described experimental setup. This is obtained by a 275 specifically conceived sharp-pointed jig which is mounted 276 on the optical head and allows for positioning by real contact 277 the head at the material interface at the exact focal distance. 278

2.2 Experimental procedures

Specimens are clamped and centered in a chuck providing the280rotational speed. They are then welded circularly in a butt joint281configuration using a continuous wave Rofin fiber laser (max-282imum power 1 kW). The optical system consisted of a 0.4-mm283fiber and two lenses of 200-mm focal and collimate lengths284which enable to deliver the laser with a minimum focal spot285



Fig. 6 Perturbation plots showing effects of all factors on a resistance length and b melting ratio

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Fig. 7 Contour graphs showing the interaction effects of *O* and *A* on **a** resistance length and **b** melting ratio



diameter of 0.4 mm. The technical details of the employedlaser welding process are shown in Table 2.

288During experimentation, O and A are selected as process 289input variables for the laser welding based on statistical factorial experimental design with full replication. Table 3 shows 290the experimental conditions, laser welding input variables, 291and design levels used at a glance. The working range for 292293 the incident angle is brought to the upper limit of 45°, for which the highest reflection is expected, while only three steps 294295are hypothesized for the offset, O. This is done to avoid insuf-296ficient melt of the martensitic steel, as testified by a preliminary set of experiments conducted with $O=300 \mu m$. 297

General full factorial design is utilized as a statistical DOE 298technique. Full factorial DOE technique relates the welding 299input parameters to each of the two output responses of the 300 weld (resistance length and melting ratio). Later, the process 301302 factors are used as input parameters to develop a mathematical model which links them to the ultimate shear strength of the 303 304 performed welds. Analysis of variance (ANOVA) and other 305 adequacy measures are used to measure the correctness of the 306 models developed and their significant linear and interaction model terms. Table 4 shows the measurement of the averaged 307 308 value of response parameters for different laser welding 309 conditions.

Argon is used as shielding gas with a constant flow rate of 6 l/min to protect weld surface from oxidation and suppresses the generation of plasma during welding. A standard ultra-312sound washing procedure is followed to clean, cool, and dry313the specimens. The experimental setup for laser welding sys-314tem is shown in Fig. 2a.315

2.3 Weld bead characterization

After welding, seam cross sections are prepared by cutting the 317 samples axially using SampleMet II (Beuhler, IL) model abra-318 sive cutter. The sectioned samples are mounted, polished, and 319chemically etched by immersion in Vilella reagent for micro-320 structural characterization. Leica IM500 software, incorporat-321 ed in an optical microscope (Leica MZ125), is used to mea-322 sure resistance length, martensitic and ferritic weld width, and 323 the area of ferrite and martensite needed to calculate the melt-324 ing ratio according to Eq. 1. 325

Experiments are replicated six times for each welding combination (A; O) to produce three specimens to be cut for metallographic analysis and three for the mechanical characterization of the weld (see Sect. 2.4). Figure 3 reports the typical cross section at the reference position and at the extreme values of the parameter tested range. 326

The guidance on quality levels for imperfections given in332ISO 13919-1:1996 [21] is followed to ensure the desired weld333quality in terms of surface cracking. At this point, each welded334specimen is visually inspected using the optical microscope.335

	TRAIN (0 11 11							
t6.1 t6.2	Table 6 Sequential model sum of squares for resistance length	Source	Sum of squares	df	Mean square	F value	P value Pr	ob>F
t6.3	model	Mean	3.292E+006	1	3.292E+006	_	_	_
t6.4		Linear	88148.54	2	44074.27	4.11	0.0538	
t6.5		2FI	64400.62	1	64400.62	16.10	0.0039	Suggested
t6.6		Quadratic	13236.46	2	6618.23	2.12	0.2017	
t6.7		Cubic	15963.75	3	5321.25	5.69	0.0936	Aliased
t6.8		Residual	2806.87	3	935.62	_	-	-
t6.9		Total	3.476E+006	12	2.897E+005	-	-	-

373

t7.1 t7.2	Table 7 Model summary statistics for resistance length model	Source	Std. dev.	R^2	Adj R ²	Pred R^2	PRESS	
t7.3	model	Linear	103.50	0.4776	0.3615	-0.1093	2.047E+005	
t7.4		2FI	63.25	0.8266	0.7615	0.5788	77734.99	Suggested
t7.5		Quadratic	55.93	0.8983	0.8135	0.6506	64492.73	
t7.6		Cubic	30.59	0.9848	0.9442	0.7809	40443.16	Aliased

336 2.4 Mechanical characterization

337 Being it impossible to obtain specimens of standard geometry (to be tested in a common shear stress test) from small size 338 339 components as the ones welded in this study, the mechanical properties of the performed joints are characterized with a 340push-out test of the internal martensitic shell with respect to 341the outer one. This test practiced on the entire assembled com-342 343 ponents allows for the characterization of the whole seam (difference in the geometry may appear during the laser power 344ramp-up or ramp down). Moreover, the constrained circular 345 configuration of the weld avoids distortions during the test, as 346 it often happens from specimen cut from a pressure vessel 347 348 (e.g., curvature problems, load misalignment due to the thickness of the shells, etc.). 349

350 All welding configurations are then tested to shear stresses under the action of a calibrated press exerting its load on a 351352 specifically conceived expeller. The photographic view in Fig. 4a shows the setup for the push-out test in which the weld 353 fails due to the disassembly forces while the model for weld 354shear failure is sketched in Fig. 4b: the draft shows the sur-355356 faces in contact during the test. The load of the press increases quasi-statically, and the maximum value generating the col-357 lapse of the joint (the ultimate shear stress) is recorded. 358

359 3 Results and discussion

The effects of individual process parameters (incidence angle
and offset) on geometrical features of the weld cross sections
(resistance length and melting ratio) are plotted by perturbation plots and described in the following sections. To

demonstrate the two-factor interaction effects on the same 364weld bead geometry, contour plots are used. Figure 3 shows 365 typical cross sections and weld profiles in the following: (a) 366 reference position and (b) the extreme values of the incidence 367 angle and the offset at the same time. It is possible to see that, 368 according to the weld design strategy described in Sect. 2.1, 369 the control of the weld position by a proper selection of input 370 parameters allows to vary the melting ratio in favor of mar-371 tensite or ferrite. 372

3.1 Visual inspection of weld quality

The reference position welding configuration shows sporadic 374superficial defects whose dimensions can be considered ac-375 ceptable according to the ISO 13919-1 standard (grade 1). 376 Results of weld seam inspection are reported in Table 5 as 377 function of the analyzed weld geometry configurations. Re-378 sults show that increasing the incident angle induces higher 379 ISO 13919 standard numbers, but increasing the offset de-380 creases the number and dimensions of microcracks. This 381means that the presence of microcracks is mainly driven by 382 the relative volume fraction of AISI 440C and AISI 430F 383 steels in the welds. Higher martensitic volume fraction in-384duces higher susceptibility to surface crack formation (tens 385 of microns length). In fact, microcracks are found to develop 386 always on the boundary of the weld seam with AISI 440C. 387

3.2 Ferritic and martensitic width (W_{\rm F} and W_{\rm M}) 388

In the reference position, the width at the free surface is nearly 389 the same for the two materials as it is possible to notice also in 390 Fig. 3a. Melt pool width on the ferritic side is slightly smaller 391

t8.1 t8.2	Table 8 Sequential model sum of squares for melting ratio model	Source	Sum of squares	df	Mean square	F value	P value Prob> F	
t8.3		Mean	14.52	1	14.52			
t8.4		Linear	7.46	2	3.73	44.42	< 0.0001	
t8.5		2FI	0.55	1	0.55	21.67	0.0016	Suggested
t8.6		Quadratic	7.083E-003	2	3.542E-003	0.11	0.8993	
t8.7		Cubic	0.13	3	0.042	1.75	0.3278	Aliased
t8.8		Residual	0.071	3	0.024	-	_	-
t8.9		Total	22.74	12	1.90	_	_	_

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t9.1	Table 9 Model summary statistics for melting ratio model								
t9.2	Source	Std. dev.	R^2	Adj R ²	Pred R^2	PRESS			
t9.3	Linear	0.29	0.9080	0.8876	0.8032	1.62			
t9.4	2FI	0.16	0.9752	0.9659	0.9420	0.48	Suggested		
t9.5	Quadratic	0.18	0.9761	0.9561	0.8979	0.84			
t9.6	Cubic	0.15	0.9913	0.9681	0.8519	1.22	Aliased		

due to the higher thermal conductivity of AISI 430F with 392 respect to AISI 440C (25 and 15 W m⁻¹ K⁻¹, respectively): 393 the ED transferred to the material can be easier conducted 394away by the outer shell. This thermal loss makes heat conduc-395tion anisotropic in the present case. The effect of increasing 396 397 the offset on the melt pool width on both sides (averaged values) is shown in Fig. 5 for different incident angles. In-398 creasing the offset obviously results in an almost linear incre-399 400 ment of ferritic width for all the incident angles, conversely for the martensitic one. Increasing the incident angle has an op-401 posite effect which compensates the asymmetry generated by 402403the use of large values of the offset, as hypothesized in Sect. 2.1. 404

The base metal microstructures are typically composed by a martensitic matrix with presence of primary and secondary Cr carbides for the AISI 440C and a ferritic matrix with elongated MnS particles for AISI 430F steel.

409 **3.3 Effects of process parameters**

410 To compare the effects of all the process parameters at the 411 center point in the design space, the perturbation plot is drawn and is shown in Fig. 6a, b. The results suggest that incidence 412angle of laser has the most significant negative impact on both 413the resistance length and MR. For melting ratio, an opposite 414 phenomenon of the same entity is observed for the offset: MR 415416 increases linearly with the increase of offset, and the two linear 417 dependencies are found to be symmetric with respect to the center point. On the other hand, the resistance length is not 418 419 remarkably affected by the change of offset, at least in the 420 tested range.

Figure 7a shows the contour plot for resistance length as a421function of interaction between offset and angle. For the initial422two levels of A (0° and 15°), S increases with the increase of O423while the opposite phenomena are observed for the other two424levels of A.425

Contour plots as shown in Fig. 7b demonstrate the fact that 426interactions of higher offset and lower incidence angle of laser 427 cause higher melting ratio. In the reference position, the aver-428aged melting ratio on the three weld specimens results MR= 4290.8: this value is lower than one which theoretically represents 430a condition of symmetry with respect to the interface between 431the two materials. Actually, the ferritic area results smaller 432than the martensitic one for all the three samples tested in 433the same condition. This phenomenon can be traced back to 434the already mentioned higher thermal conductivity of AISI 435430F which favors heat conduction away from the irradiated 436 area. As a result, the melt pool develops more on the AISI 437440C area and makes this material, which is also characterized 438by a much more brittle microstructure, more susceptible to 439cracking. Thus, it should be taken into account that even in a 440 symmetric configuration, like the reference position, the weld 441 pool develops in asymmetric way due to the different thermal 442 properties of the two dissimilar metals. MR increases almost 443 linearly with the offset for each incidence angle: it especially 444increases faster for 0° and 15° for which the percentage of 445melt ferrite more than doubles. For the higher values of A, 446 the direction of the beam axis, pointing to the martensitic steel, 447 compensates the effect of the offset and the rate of growth of 448 the ferritic area is less pronounced. 449

3.4 Development of mathematical models

At this stage, the fit summary in the Design-Expert software 451V7 is used to select the models that best describe the response 452factors. The fit summary includes sequential model sum 453squares to select the highest order polynomial where addition-454al terms are significant and the model is not aliased. In addi-455tion, model summary statistics of the fit summary focuses on 456the model that maximizes adjusted R^2 and predicted R^2 values. 457The sequential F test and lack-of-fit test are carried out using 458the same statistical software package to check if the regression 459

t10.1 Table 10 ANOVA table for t10.2 resistance length 2FI model	Source	Sum of squares	df	Mean square	F value	P value Prob> F	
t10.3	Model	1.525E+005	3	50849.72	12.71	0.0021	Significant
t10.4	0	1128.13	1	1128.13	0.28	0.6098	
t10.5	A	87020.42	1	87020.42	21.75	0.0016	
t10.6	OA	64400.62	1	64400.62	16.10	0.0039	
t10.7	Residual	32007.08	8	4000.89			
t10.8	Cor total	1.846E+005	11				

 $R^2 = 0.8266$, adj $R^2 = 0.7615$, pred $R^2 = 0.5788$, adeq precision=12.85

t11.1 Table 11 ANOVA table for t11.2 melting ratio 2FI model	Source	Sum of squares	df	Mean square	F value	P value Prob> F	
t11.3	Model	8.02	3	2.67	104.87	< 0.0001	Significant
t11.4	0	3.51	1	3.51	137.81	< 0.0001	-
t11.5	A	3.95	1	3.95	155.13	< 0.0001	-
t11.6	OA	0.55	1	0.55	21.67	0.0016	-
t11.7	Residual	0.20	8	0.025	_	-	-
t11.8	Cor total	8.22	11	_	_	_	-

 $R^2 = 0.9752$, adj $R^2 = 0.9659$, pred $R^2 = 0.9420$, adeq precision=31.088

460 model is significant and to find out the significant model terms
461 of the developed models as well. The stepwise regression
462 method is also applied to eliminate the insignificant model
463 terms automatically.

464 Suitable response models for the response factors are se-465 lected based on the fit summaries. From fit summary output of 466 the measured responses shown in Tables 6, 7, 8, and 9, it is 467 evident that two-factor interaction (2FI) models are statistical-468 ly recommended for further analyses of both the resistance 469 length and melting ratio.

The test for significance of the regression models and the 470471 test for significance on individual model coefficients are per-472 formed using the same statistical package. By selecting the 473 stepwise regression method that eliminates the insignificant 474model terms automatically, the resulting ANOVAs in Tables 10 and 11 for the selected models summarize the 475ANOVA of each response and illustrate its significant model 476 terms as well. The aforestated tables demonstrate that calcu-477 478 lated Fisher's "Model-F" and "Model-P" values are, respec-479tively, 12.71 and 0.0021 for resistance length's 2FI model and 480 104.87 and <0.0001 for melting ratio 2FI model. These Model-F and Model-P values imply that the selected models 481 are highly significant and there is only 0.21 % and a less than 482

0.01 % chance that these large Model-F values could occur483due to noise. The associated P value is also used to estimate484whether F is large enough to indicate statistical significance. If485P value is lower than 0.05, it indicates that the model is statistically significant as stated by Zulkali et al. [24].487

Tables 10 and 11 also show other adequacy measures, e.g., 488 R^2 , adjusted R^2 , and predicted R^2 values. All the adequacy 489measures are in logical agreement and indicate significant 490relationships. Moreover, adequate precision compares range 491of predicted value at the design points to average prediction 492error. The adequate precision ratios in all cases are dramati-493cally greater than 4 indicating adequate model discrimination. 494Again, the ANOVA tables for the resistance length model and 495melting ratio model show that all two linear terms, i.e., offset 496and laser incident angle and two-factor interactions (2FI) of 497offset-angle (O-A), are significant model terms. From the re-498sults shown in Tables 6, 7, 8, 9, 10, and 11, it is, therefore, 499apparent that the developed statistical models for predicting 500resistance length and melting ratio are fairly accurate and can 501be of following forms: 502

1. Resistance length, $S=523.75-11.87 \times O-114.25 \times A+$ 503 120.37× $O \times A$ 504



Fig. 8 Normal probability plot for a resistance length and b melting ratio

Fig. 9 Scatter diagrams of a resistance length and b melting ratio



505 2. Melting ratio, MR=1.1+0.66 $\times O$ -0.77 $\times A$ -0.35 $\times O \times A$

Normality of residual data and amount of residuals in pre-506diction are then checked to ensure statistical validation of the 507508developed models. The normality of data is verified by plotting the normal probability plot (NPP) of residuals. The resid-509510ual is the difference between observed and predicted values (or fitted value) obtained from the regression model. The data 511set is normally distributed if the points on the plot fall fairly 512close to the straight line. The NPPs of residual values for weld 513resistance length and melting ratio are depicted in Fig. 8a, b, 514515respectively. The experimental points are reasonably aligned

t12.1 Table 12 Summary of results of investigated parameters

t12.2	Welding configuration	Averaged melting ratio, MR (a.u.)	Carbon in melting pool (%)	Averaged resistance length, S (µm)	Surface cracks ^a	Averaged USF (N)
t12.3	1	0.8	0.66	760	1	4900
t12.4	2	2.0	0.45	695	0	4380
t12.5	3	2.7	0.38	465	0	4180
t12.6	4	0.5	0.77	535	3	3825
t12.7	5	1.6	0.49	610	0	4200
t12.8	6	2.2	0.43	450	0	4020
t12.9	7	0.3	0.87	480	3	3550
t12.10	8	0.6	0.73	550	2	3940
t12.11	9	1.5	0.51	590	0	4540
t12.12	2 10	0.1	1.01	280	3	2710
t12.13	3 11	0.3	0.87	415	3	3650
t12.14	12	0.6	0.73	455	2	4090

All data refer to the average value of three specimens. Values are attributed according to ISO 13919-1:1996 [17], after inspection on the three samples for each configuration

^a0=no defects, 1=exist but acceptable, 2-3=not acceptable

with predicted or fitted points suggesting the normality of
data. This is an implication that empirical distribution of re-
sidual data is well compared with a normal distribution having
the same mean and variance.516
517

Figure 9a, b shows the relationships between the actual and 520predicted values of weld resistance length and melting ratio. 521Since the points plotted are close to and around the diagonal 522line, the difference between the predicted and actual values for 523each point can be considered to be minimal. It is also an 524indication that the statistical models for prediction are ade-525quate and predicted results are in good agreement with the 526measured data. 527

3.5 Ultimate shear force

The value of the ultimate force making the weld collapsing 529under shear stresses, averaged for the three tested samples, is 530reported in Table 12 along with all the other investigated pa-531rameters (S, MR, crack grade). All failure data reported in 532Table 12 (under the column "Averaged ultimate shear force 533(USF)") are related to a brittle fracture of the weld. The ap-534plied load increases quasi-statically with increasing the appli-535cation time up to the moment in which the fracture propagates 536drastically over the 360° detaching the two components. 537

The averaged MR gives an indication of the carbon 538content of the fusion zone (also reported in the table), 539where the chemical composition is the average between 540the two base steels weighted for their volume fraction. 541This is because, as reported in Table 1, the other main 542element (chromium, manganese, and silicon) concentra-543tions are almost the same for the two welded steels; thus, 544the properties of the melting pool are driven by the carbon 545content. It ranges between 0.4 and 1 % for the highest and 546lowest measured MR values, respectively. 547

According to the literature [15, 25], the USF linearly depends on the dimension of the resistance length. The highest 549



Fig. 10 Ultimate shear force of the fusion zone as a function of melting ratio

550USF is then obtained in the reference position for which the resistance length has the highest value within the tested range. 551Nevertheless, a second important effect on USF can be also 552noticed referring to those configurations having a nearly same 553resistance length but different melting ratio. Considering only 554the linear dependence of USF on the resistance length, 555those configurations having a similar S ($\pm 10 \mu m$) should 556557break under a similar load. Conversely, Table 12 shows that configurations 3 and 6 result in a sensible higher USF 558in respect to 7 and 12 for which the percentage of mar-559560tensitic material in the melt pool is higher.

Figure 10 representing the behavior of USF as a function of
the melting ratio obviously includes also the dependence on S.
In order to give evidence on how the melting ratio influences
the USF, couples of welding configurations having the same S

but different MR have to be considered. As an example, 565welding configuration numbers 3 and 6 (see Table 12) with 566 MR=(2.7-2.2), respectively, and $S=(450-460)\mu m$ can be 567compared to numbers 7 and 12 (obtained with large A): 568 $S=(450-480 \text{ }\mu\text{m})$ but opposite MR=(0.3-0.6) as indicated by 569arrows in Fig. 10. Measured data reveal that increasing the 570volume fraction of the ferritic stainless steel in the melt pool 571has beneficial aspects on the ultimate shear strength. Also, data 572dispersion (with respect to the averaged value reported in Ta-573ble 12) decreases with increasing MR, making the failure mode 574more predictable. This means that the prevailing effect is the 575decreased brittleness of the weld by decreasing its carbon con-576tent. In fact, high carbon content in the melt pool not only 577 increases the crack susceptibility but also lowers the USF. 578

Experimental results suggest the use of welding configura-
tions generating MR \geq 1.5 to obtain a crack-free surface (grade
0 according to the ISO 13919-1 standard) and to ensure high
and well-reproducible USF.581
582

An attempt to link mathematically the USF to the parameters which determine the welding configuration is developed 584 by means of the full factorial DOE. 585

$$JSF = 1408.18 + 4778.52 \times O + 940.85 \times A - 1562.99 \\ \times O \times A$$
588

The NPP of residual values for USF is depicted in Fig. 11. **589** The experimental points are reasonably aligned with predicted 590 or fitted points suggesting the normality of data. This is an implication that empirical distribution of residual data is well 592 compared with a normal distribution having the same mean and variance. 594

Figure 12 shows the relationships between the actual and 595 predicted values of weld USF. Since the points plotted are close to and around the diagonal line, the difference between 597 the predicted and actual values for each point can be 598



Fig. 11 Normal probability plot weld USF



Fig. 12 Scatter diagram of USF

599 considered to be minimal. From Fig. 12, it is clear that the 600 predicted results are in good agreement with the measured 601 data for USF.

602 4 Conclusions

Ferritic AISI 430F and martensitic AISI 440C stainless steel 603 604 shells have been laser welded in constrained butt configura-605 tion. The effects of different combination of incident angles 606 and offsets have been studied, analyzing the following parameters of the fusion zone: cross-sectional geometry (resistance 607 length and width at the free surface), melting ratio between the 608 dissimilar steels, presence of surface cracks and relative di-609 mensions, and ultimate shear strength of the welds. For the 610 611 laser system, weld joint type, and the limits of laser parameters 612 considered in this study, the following points can be 613 concluded:

- 614The presence of surface cracks is more relevant when the615melting ratio is lower than 0.8 (reference position). This is616more evident with incident angles of 30° and 45°, al-617though some mitigations could be obtained by increasing,618at the same time, the offset value. It was shown that the619welding configuration controls the geometry of the weld620and the mixing between the dissimilar steels which influ-
- 621 ences strength and brittleness of the seam.
- 622Both resistance length and melting ratio can be readily623linked to laser offset and incidence angle at the shell624interface by using a linear regression over the experimen-625tal data. Remarkably, the melting ratio is a good indicator626of the carbon content on the fusion zone and the critical627value MR=1.5 is related to carbon content in the fusion628zone of about 0.5 %.
- Well-reproducible USF in the range of 4.5-4 kN can be 629 obtained with welding configurations generating MR 630 631 >1.5 with an almost negligible incidence of surface cracks (grade 0 according to the ISO 13919-1 standard). 632 It was proved that the ultimate shear strength is not only 633 634 linearly dependent on the resistance length but also susceptible to the micromechanical properties of fusion zone 635(especially brittleness) and, thus, to the melting ratio. 636 637 Measured data revealed that it is possible to find an empirical relationship between the shear strength of the weld 638 and the configuration adopted during experiments by 639 640 using full factorial DOE.

These conclusions pinpointed for the welding conditions
under investigation can be easily extended to a broader range
of weld designs under the limiting condition that the formation
of the weld bead is conduction dominated and plasma formation is not considered.

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