# Multi-objective optimization of steel fusion welding

P. Cavaliere, A. Perrone
*Department of innovation engineering, University of Salento, Lecce (Italy)*
*pasquale.cavaliere@unisalento.it*

**ABSTRACT.** Steel fusion welding is characterized by phase transformations influencing the final mechanical properties. Such properties and modifications are strongly related to welding parameters such as speed, current, voltage and heat input. In the present paper hardness, residual stresses, phase transformations, tensile, fatigue and impact properties of different steel welds have been related to the material composition, geometry and the welding conditions by employing a multi objective optimization software (modeFRONTIER$^{(R)}$). As a matter of fact the weight of the different parameters influence have been evaluated through such kind of study. An optimization analysis have been performed in order to identify the best welding condition for each kind of steel taking as final goal the fatigue and impact strength of the joints.

**SOMMARIO.** I giunti fusori sono caratterizzati da notevoli trasformazioni di fase che influenzano fortemente le proprietà meccaniche finali. Tali proprietà sono fortemente legate ai parametri di processo quali velocità di saldatura, corrente, voltaggio e densità d'energia. Nel presente studio le caratteristiche meccaniche (durezza, tensioni residue, fatica, resistenza all'impatto) di divesi giunti in acciaio sono state correlate alla composizione dei materiali, geometrie, condizioni di saldatura attraverso l'utilizzo di un codice di calcolo di ottimizzazione multiobiettivo. Per ogni singolo acciaio si sono identificate le condizioni ottimali di saldatura per l'ottenimento delle migliori prestazioni in funzione delle caratteristiche di resistenza in trazione, fatica e resistenza all'impatto.

**KEYWORDS.** welding, steel, multi-objective optimization, fatigue, impact strength.

## INTRODUCTION

Actually, very few information are available on the microstructure-fracture-fatigue properties of fusion welded joints in the open literature. The practical application of any steel on a larger scale is critically dependent on its weldability for fabrication [1]. The optimum correlation of microscopic-mechanical properties of welded structures is intimacy related to the processing parameters such as welding speed, heat input and geometry [2]. Meanwhile, very few data are available on the composition-fusion zone-HAZ-mechanical properties correlations especially in the case of multi pass gas metal arc welding, the microstructures that form in the Heat Affected Zone (HAZ) are highly heterogeneous due to the different heating/cooling rates experienced at various distances from the fusion line [3, 4]. In all arc-welding processes, the high heat source produced by the arc and the associated local heating and cooling result in a number of consequences in material behavior and several metallurgical phase changes occur in different zones of a weldment. The microstructure and stress state characteristics of the welded joints differ from those of the base material, and the performance of the welded structure is usually limited by the initiation of failure within the Heat Affected Zone (HAZ) of the base material, particularly within the coarse-grained region of the HAZ adjacent to the weld metal. Therefore, to ensure the reliability of large-scale structures which will be subjected to dynamic impact loading conditions, it is essential to evaluate the mechanical properties of their structural materials, including their weld metals [5]. For each kind of steel is fundamental the individuation of the achievement of the optimal microstructure in terms of phases and residual stresses [6-8]. The deep analysis of industrial processes depending on different parameters necessitate the employment of computational multi objective optimization tools. Optimization is achievable through integration with multiple calculation tools and explicable by effective post-processing tools. The progresses of high performance computing offer the availability of accurate and reliable virtual environments to explore several possible configurations. These factors lead to a Design of Experiment (DOE) technique to perform a reduced number of calculations. After that, these well-distributed results can be used to create an interpolating surface. This surface represents a meta-model of the original problem and can be used to perform the optimization without computing any further analyses. Once data has been obtained, whether from an optimization or DOE, or from data importation, the user can turn to the extensive post-processing features to analyze the results. Desing of Experiments (DOE) is a methodology that maximizes the knowledge gained from experimental data. It provides a strong tool to design and analyze experiments, it eliminates redundant observations and reduces the time and resources to make experiments. The paper presents the results of a broad experimental campaign performed on different steel joints obtained with different processing parameters with a special focus on the resulting microstructural properties and consequently mechanical properties; the data were employed to build a predictive database through a numerical multi-objective optimization tool.

## EXPERIMENTAL PROCEDURE

Starting from a datebase built with experimental results, they were developed computational models (virtual n-dimensional surfaces) able to reproduce at best the actual process. Trough such analysis it was possible to optimize the output variables hardness profiles, residual stresses, phase transformations, tensile, fatigue and impact properties).
The method used for the creation of meta-models to simulate the actual process through the use of physical laws with appropriate coefficients to be calibrated was that of the RSM (Responce Surface Methodology).
This method consists of creating n-dimensional surfaces that are "trained" on the basis of actual input and output. These surfaces trained on a large experimental data can give the output numbers that reflect the real process of welding.

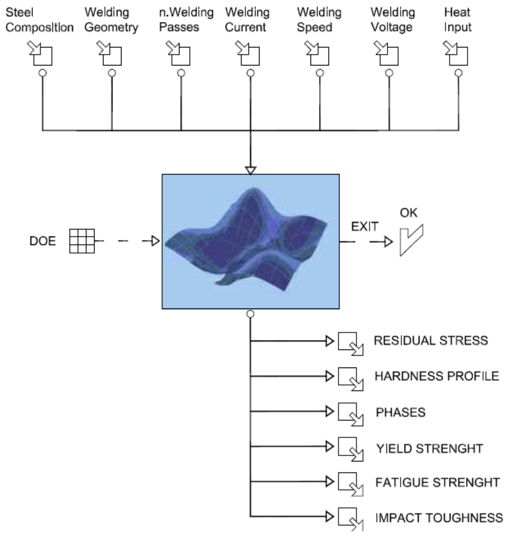


Figure 1: Workflow of analysis.

The experimental design consists of 600 input and output obtained from experimental data. To train the virtual surface in the training phase they were included 580 experimental design input and output. The remaining 20 we used in the design validation phase. In the validation phase, they were included in the RSM "trained" only the input remaining conditions and they were compared the numerical calculated output with the experimental output, measuring the Δ error. The phase of the training and validation are the Design of Experiment (DOE). The welding process through the analysis performed by Mode FRONTIER is summarized in the Workflow of Fig. 1. The workflow is divided into data flow (solid lines) and logic flow (dashed lines) that have as their common node the computer node in which to introduce physical and mathematical functions representing the nitriding process. In the data flow they are included all input parameters

optimized in the numerical simulations: Steel composition, Welding geometry, Number of welding passes, Welding current, Welding speed, Welding voltage, Heat input
And those output: Residual stresses, Hardness profiles, Phase transformations, Tensile strength, Fatigue strength, Impact toughness. The output variables define a multi goal analysis and have been minimized taking into account some constraints or limitations typical of the actual process. At this stage the nodes that make up the logic flow of numerical analysis are defined. The first node is the DoE, which is the set of different designs reproducing different possible working conditions, among which the most affective ones are highlighted. Therefore it means creating a set number of designs that will be used by the scheduler (the node where the best algorithm is introduced) for the optimization. The database is built by introducing the input parameters, the corresponding output for each working condition experimentally analyzed and the physical correlations between the different conditions. The steel composition was taken into account in the calculations; the employed welding conditions are summarized in Tab. 1.

Weld EXP DATA

| AISI | UNI | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 28 | 29 | 30 | 31 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | S | S1 | alfa | B | L1** | L2 | pp_n_p_TOT | pp_n_p | pp_I | pp_speed | pp_V | pp_Q |
| | | mm | mm | deg | mm | mm | mm | - | - | A | cm/min | V | kJ/cm |
| 1020 | C20 | 80 | 14 | 70 | 1 | 200 | 200 | 11 | 1 | 780 | 50 | 30 | 28.1 |
| 1045 | | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 780 | 50 | 30 | 28.1 |
| 304 | X5CrNi1810 | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 200 | 8 | 12 | 18 |
| 316 | X5CrNiMo17 12 | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 156 | 10 | 12.5 | 11 |
| 409M | | 6 | 1 | 70 | 0.2 | 100 | 100 | 2 | 1;2 | 120 | 24 | 25 | 6.5 |
| 321 | X6CrNiTi1811 | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 120 | 7 | 22 | 22 |
| 4340 | | 14 | 2 | 70 | 0.2 | 100 | 100 | 3 | 1;3 | 170 | 12 | 26 | 16 |
| SAF2205 | | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 28 | 17.4 | 150 | 10 |
| SAF 2507* (inossidabili superduple | | 10 | 3 | 60 | 0.2 | 100 | 100 | 3 | 1;4 | 61 | 8 | 13.5 | 6 |
| | TstE420 | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 23 | 17.4 | 140 | 11 |
| | MIL-A-11356F | 80 | 14 | 70 | 1 | 200 | 200 | 17 | 1 | 70 | 17.4 | 170 | 10 |
| | RQT701 | 8 | 1.5 | 70 | 0.2 | 100 | 100 | 2 | 1;2 | 339 | 20 | 30 | 30 |
| | 91CrMo-NbV | 6 | 1 | 70 | 0.2 | 100 | 100 | 2 | 1;2 | 300 | 30 | 30 | 12 |
| | Weldox1100E | 5.5 | 1 | 50 | 0.2 | 100 | 100 | 3 | 1;2 | 150 | 26 | 19 | 6.5 |
| | Weldox960E | 5 | 1 | 50 | 0.2 | 100 | 100 | 3 | 1;2 | 150 | 27 | 19 | 6.6 |
| | X65 | 80 | 14 | 70 | 1 | 200 | 200 | 11 | 1 | 780 | 50 | 30 | 28.1 |
| | Fe-Mn | 40 | 7 | 35 | 1 | 200 | 200 | 16 | 1;2 | 260 | 18 | 28 | 24 |
| HSLA | | 16 | 2 | 70 | 0.2 | 100 | 100 | 3 | 1;3 | 500 | 30 | 25 | 30 |
| HSLA100 | | 25 | 3 | 70 | 1 | 100 | 100 | 14 | R;13 | 500 | 24 | 35 | 20 |
| HSLA80 | | 12 | 2 | 70 | 0.2 | 100 | 100 | 3 | 1;3 | 160 | 13 | 24 | 13 |
| | XCrNi13-4 | 52 | 10 | 70 | 1 | 200 | 200 | 17 | 1 | 150 | 12 | 26 | 25 |

| AISI | UNI | 33 | 35 | 36 | 37 | 38 | 40 | 42 | 43 | 44 | 45 | 47 | 49 | 50 | 51 | 52 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | pp_n_p | pp_I | pp_speed | pp_V | pp_Q | pp_n_p | pp_I | pp_speed | pp_V | pp_Q | pp_n_p | pp_I | pp_speed | pp_V | pp_Q |
| | | - | A | cm/min | V | kJ/cm | - | A | cm/min | V | kJ/cm | - | A | cm/min | V | kJ/cm |
| 1020 | C20 | 2;7 | 650 | 60 | 30 | 20.8 | 8;10 | 650 | 60 | 30 | 20.8 | R | 780 | 50 | 33 | 30.9 |
| 1045 | | 2;12 | 730 | 50 | 33 | 28.9 | 13-16 | 730 | 50 | 33 | 28.9 | R | 780 | 50 | 33 | 30.9 |
| 304 | X5CrNi1810 | 2;12 | 170 | 8 | 11 | 14 | 13-16 | 170 | 8 | 11 | 14 | R | 200 | 8 | 12 | 18 |
| 316 | X5CrNiMo17 12 | 2;12 | 156 | 11 | 12.5 | 11 | 13;16 | 156 | 11 | 12.5 | 11 | R | 156 | 10 | 12.5 | 11 |
| 409M | | | | | | | | | | | | | | | | |
| 321 | X6CrNiTi1811 | 2;12 | 120 | 7 | 22 | 22 | 13;16 | 120 | 7 | 22 | 22 | R | 120 | 7 | 22 | 22 |
| 4340 | | | | | | | | | | | | | | | | |
| SAF2205 | | 2;12 | 136 | 17.4 | 150 | 10 | 13;16 | 28 | 17.4 | 150 | 10 | R | 28 | 17.4 | 150 | 10 |
| SAF 2507* (inossidabili superduple | | | | | | | | | | | | | | | | |
| | TstE420 | 2;12 | 156 | 17.4 | 140 | 11 | 13;16 | 23 | 17.4 | 140 | 11 | R | 23 | 17.4 | 140 | 11 |
| | MIL-A-11356F | 2;12 | 70 | 17.4 | 170 | 10 | 13;16 | 70 | 17.4 | 170 | 10 | R | 70 | 17.4 | 170 | 10 |
| | RQT701 | | | | | | | | | | | | | | | |
| | 91CrMo-NbV | | | | | | | | | | | | | | | |
| | Weldox1100E | 3 | 150 | 28 | 19 | 6.1 | | | | | | | | | | |
| | Weldox960E | 3 | 124 | 21 | 16.8 | 6 | | | | | | | | | | |
| | X65 | 2;7 | 650 | 60 | 30 | 20.8 | 8;10 | 650 | 60 | 30 | 20.8 | R | 780 | 50 | 33 | 30.9 |
| | Fe-Mn | 3;7 | 320 | 30 | 25 | 23 | 8;14 | 330 | 32 | 25 | 25 | 0 | 0 | 0 | 0 | 0 |
| HSLA | | | | | | | | | | | | | | | | |
| HSLA100 | | | | | | | | | | | | | | | | |
| HSLA80 | | | | | | | | | | | | | | | | |
| | XCrNi13-4 | 2;12 | 150 | 12 | 26 | 25 | 13;16 | 150 | 12 | 26 | 25 | R | 150 | 12 | 26 | 25 |

Table 1: Welding input for each studied steel.

Depending on the steel, different thicknesses in the range 2-80 mm were produced via gas metal arc welding (GMAW). Different welding parameters were employed and different number of passes for the same weld geometry. Tensile, fatigue, impact tests were performed on all the samples; residual stresses were measured through x-rays diffraction; weld phases were characterized through optical microscopy observations.

## RESULTS AND DISCUSSION

The output results corresponding to the steel compositions and input parameters previous showed are listened in Tab. 2. Many different considerations can be done on the general output belonging to the present analysis, microhardness increses as increasing $\alpha$ up to 70°and then decreases as increasing $\alpha$; for each different steel, microhardness is higher for the thicker weld plate. By observing the other mechanical properties, it can be noted that microhardness increases as increasing impact strength, residual stresses and UTS up to intermediate values and then decreases. The impact strength increases as increasing $\alpha$ and voltage and decreases as increasing the welding passes. The impact strength is optimal for intermediate values of yield strength and UTS. In the present study response surfaces that are best suited to deal with a multi-objective optimization were obtained. The response surfaces are a function of the chosen response surface. It is also important, in the present analysis, to employ the so called "correlation matrix" that allows to immediately recognize how much the different variables are correlated between them, actually the parameters are strongly correlated if the corresponding value in the table are distant from zero in a range between -1 and 1, if the value is 1 the parameters are directly correlated, while if the value is -1 the parameters are inversely correlated. An example for the present study is given in the following figure, from such matrix it is also possible to observe the different weight of all the parameters, the more the value differs from 0 the more it influence the corresponding variable (Fig. 2).

| Weld EXP DATA | | residual stresses | | | | hardness | | | | phases | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 54 | 58 | 63 | 68 | 99 | 103 | 108 | 113 | | | | | | | | | | |
| | | RS_A1 | RS_A5 | RS_A10 | RS_A15 | Hv_A1 | Hv_A5 | Hv_A10 | Hv_A15 | M_s_A | M_f_A | B_s_A | B_f_A | P_s_A | P_f_A | F_s_A | F_f_A | A_s_A | A_f_A |
| AISI | UNI | Mpa | Mpa | Mpa | Mpa | | | | | mm | mm | mm | mm | mm | mm | mm | mm | mm | mm |
| 1020 | C20 | 90 | 510 | 520 | 80 | 165 | 213 | 218 | 154 | | | 11 | 13 | 8 | 15 | 11 | 13 | | |
| 1045 | | 110 | 550 | 550 | 170 | 170 | 228 | 218 | 165 | | | 8 | 11 | 13 | 15 | 10 | 11 | | |
| 304 (inossidabili aust.) | X5CrNi1810 | -80 | 190 | 255 | -75 | 220 | 255 | 275 | 225 | | | | | | | 8 | 12 | 8 | 15 |
| 316 (inossidabili aust.) | X5CrNiMo17 12 | -95 | 215 | 280 | -100 | 160 | 245 | 250 | 165 | | | | | | | 8 | 13 | 8 | 15 |
| 409M | | 20 | 240 | 240 | 30 | 340 | 265 | 200 | 340 | 8 | 12 | | | | | 8 | 15 | 8 | 9 |
| 321 | X6CrNiTi1811 | -65 | 185 | 320 | -60 | 145 | 130 | 460 | 150 | 8 | 10 | | | | | 8 | 15 | 8 | 9 |
| 4340 | | 210 | 130 | 130 | 210 | 450 | 260 | 265 | 450 | 8 | 15 | | | | | 8 | 11 | 8 | 11 |
| SAF2205 (inossidabili duplex) | | 30 | 150 | 210 | 50 | 250 | 230 | 240 | 250 | | | | | | | 8 | 15 | 8 | 15 |
| SAF 2507* (inossidabili superduplex) | | 0 | 45 | 70 | 0 | 270 | 270 | 285 | 270 | | | | | | | 8 | 15 | 10 | 15 |
| | TstE420 | -40 | 190 | 210 | -60 | 370 | 270 | 260 | 360 | | | 8 | 13 | | | 8 | 15 | | |
| | MIL-A-11356F | 15 | 150 | 200 | 35 | 270 | 302 | 295 | 270 | 8 | 11 | 10 | 13 | 13 | 15 | | | | |
| | RQT701 | -60 | 75 | 220 | -20 | 270 | 350 | 355 | 290 | 8 | 11 | 8 | 12 | 12 | 15 | 8 | 12 | | |
| | 91CrMo-NbV | -70 | 110 | 150 | -50 | 210 | 200 | 220 | 210 | 8 | 15 | | | 13 | 15 | 8 | 12 | | |
| | Weldox1100E | 100 | 180 | 180 | 80 | 450 | 325 | 375 | 450 | 8 | 15 | 8 | 11 | | | | | | |
| | Weldox960E | 0 | 160 | 270 | 80 | 350 | 350 | 300 | 350 | 8 | 15 | 8 | 10 | | | | | | |
| | X65 | -40 | 240 | 220 | -20 | 206 | 217 | 225 | 206 | | | 8 | 11 | 11 | 15 | 8 | 11 | | |
| | Fe-Mn | 30 | 145 | 175 | 20 | 150 | 245 | 260 | 150 | | | 8 | 12 | 13 | 15 | 8 | 12 | | |
| HSLA | | -30 | 100 | 110 | -30 | 190 | 280 | 280 | 190 | | | 8 | 11 | | | 8 | 15 | | |
| HSLA100 | | -50 | 230 | 380 | -50 | 250 | 250 | 290 | 250 | | | 8 | 11 | | | 8 | 15 | | |
| HSLA80 | | -185 | -150 | 70 | -170 | 305 | 280 | 280 | 305 | | | 8 | 13 | | | 8 | 15 | | |
| | XCrNi13-4 | -30 | 240 | 380 | -20 | 260 | 280 | 280 | 260 | 8 | 15 | | | | | 8 | 12 | | |

| Weld EXP DATA | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 144 | 145 | | | | | | | 146 | | | | | 147 | |
| | | UTS(Base) | YTS | UTS | R | UTS/3 = $\Delta\sigma_a$ | $\Delta\sigma_{a,t}$ | $\Delta\sigma_{TEST}$ | $\sigma_{MAX,TEST}$ | Nf | Ldf (R=0.1) | σmax | σmin | σmed | max-σme | Kv | MinKv(Base) |
| AISI | UNI | Mpa | Mpa | Mpa | | Mpa | Mpa | Mpa | Mpa | | Mpa | | | | | J | J |
| 1020 | C20 | 420 | 500 | 525 | 0.1 | 140 | 104.7 | 125.6 | 139.57 | 2000000 | 200 | 220 | 20 | 120 | 100 | 154 | 135 |
| 1045 | | 720 | 510 | 545 | 0.1 | 240 | 179.4 | 215.3 | 239.26 | 2000000 | 304 | 334.4 | 30.4 | 182.4 | 152 | 121 | 110 |
| 304 (inossidabili aust.) | X5CrNi1810 | 622 | 610 | 680 | 0.1 | 207.33333 | 155 | 186 | 206.69 | 2000000 | 270 | 297 | 27 | 162 | 135 | 66 | 85 |
| 316 (inossidabili aust.) | X5CrNiMo17 12 | 665 | 620 | 695 | 0.1 | 221.66667 | 165.7 | 198.9 | 220.98 | 2000000 | 250 | 275 | 25 | 150 | 125 | 80 | 64 |
| 409M | | 480 | 205 | 255 | 0.1 | 160 | 160 | 192 | 213.33 | 2000000 | 200 | 220 | 20 | 120 | 100 | 42 | 22 |
| 321 | X6CrNiTi1811 | 651 | 530 | 590 | 0.1 | 217 | 162.2 | 194.7 | 216.33 | 2000000 | 312 | 343.2 | 31.2 | 187.2 | 156 | 135 | 128 |
| 4340 | | 760 | 620 | 650 | 0.1 | 253.33333 | 253.3 | 304 | 337.78 | 2000000 | 403 | 443.3 | 40.3 | 241.8 | 201.5 | 124 | 132 |
| SAF2205 (inossidabili duplex) | | 765 | 500 | 572 | 0.1 | 255 | 190.7 | 228.8 | 254.21 | 2000000 | 340 | 374 | 34 | 204 | 170 | 81 | 100 |
| SAF 2507* (inossidabili superduplex) | | 879 | 640 | 680 | 0.1 | 293 | 293 | 351.6 | 390.67 | 2000000 | 360 | 396 | 36 | 216 | 180 | 116 | 150 |
| | TstE420 | 620 | 540 | 604 | 0.1 | 206.66667 | 154.5 | 185.4 | 206.03 | 2000000 | 250 | 275 | 25 | 150 | 125 | 190 | 240 |
| | MIL-A-11356F | 690 | 530 | 592 | 0.1 | 230 | 172 | 206.4 | 229.29 | 2000000 | 276 | 303.6 | 27.6 | 165.6 | 138 | 59 | 90 |
| | RQT701 | 920 | 663 | 944 | 0.1 | 306.66667 | 306.7 | 368 | 408.89 | 2000000 | 400 | 440 | 40 | 240 | 200 | 54 | 40 |
| | 91CrMo-NbV | 585 | 325 | 375 | 0.1 | 195 | 195 | 234 | 260 | 18632 | 180 | 198 | 18 | 108 | 90 | 19 | 112 |
| | Weldox1100E | 1250 | 1080 | 1190 | 0.1 | 416.66667 | 416.7 | 500 | 555.56 | 2000000 | 546 | 600.6 | 54.6 | 327.6 | 273 | 102 | 120 |
| | Weldox960E | 1000 | 1000 | 1040 | 0.1 | 333.33333 | 333.3 | 400 | 444.44 | 2000000 | 459 | 504.9 | 45.9 | 275.4 | 229.5 | 75 | 95 |
| | X65 | 530 | 440 | 510 | 0.1 | 176.66667 | 132.1 | 158.5 | 176.12 | 2000000 | 260 | 286 | 26 | 156 | 130 | 70 | 100 |
| | Fe-Mn | 680 | 585 | 630 | 0.1 | 226.66667 | 201.5 | 241.8 | 268.72 | 2000000 | 336 | 369.6 | 33.6 | 201.6 | 168 | 95 | 80 |
| HSLA | | 765 | 580 | 640 | 0.1 | 255 | 255 | 306 | 340 | 2000000 | 425 | 467.5 | 42.5 | 255 | 212.5 | 65 | 100 |
| HSLA100 | | 860 | 900 | 940 | 0.1 | 286.66667 | 286.7 | 344 | 382.22 | 2000000 | 462 | 508.2 | 46.2 | 277.2 | 231 | 125 | 150 |
| HSLA80 | | 815 | 810 | 890 | 0.1 | 271.66667 | 271.7 | 326 | 362.22 | 2000000 | 448.5 | 493.4 | 44.85 | 269.1 | 224.25 | 110 | 115 |
| | XCrNi13-4 | 980 | 640 | 740 | 0.1 | 326.66667 | 272 | 326.4 | 362.68 | 2000000 | 440 | 484 | 44 | 264 | 220 | 40 | 80 |

Table 2: Welding output for each studied steel.

By looking at the mechanical properties of the weld it can be observed that Yield strength is strongly inversely dependent on ferritic and perlitic microstructure and less from bainitic or austenitic microstructure; it is also dependent (with the same weight) inversely from heat input and residual stresses. Impact strength seems to be influenced by perlitic microstructure and inversely proportional to heat input. Fatigue life is strongly directly proportional to yield strength, then it is inversely proportional to ferritic and perlitic microstructure, it is directly proportional to martensitic microstructure and it is directly proportional to impact strength, such result is very important because by tuning the processing parameters in order to achieve high yield strength and impact strength of the welds, at the same time it is possible to achieve good fatigue strength of the joints. The analysis of fatigue data is difficult to perform by considering all the steels together, for this reason an evaluation of the effect of input parameters and other mechanical properties on the fatigue life has been performed for each single steel. For the AISI 1020, 1045, 409M, 4340, HSLA100 and Weldox1100E alloys it can be observed that The fatigue limit increases as increasing the residual stresses and decreasing of the heat input. The same behavior is observed for the X5CrNi1810, in such case the fatigue strength reaches good levels in a broad range of residual stresses and heat input. For the X5CrNiMo1712 and X6CrNiTi1811 the fatigue limit is maximum at intermediate residual stresses and high heat input. The fatigue limit is high for high levels of impact strength and intermediate values of heat input for AISI 1020, for the AISI1045 and AISI 4340 the fatigue limit and impact strength are high for low heat input. For the X5CrNi1810, X5CrNiMo1712, HSLA100 and Weldox1100E the fatigue limit is high for very high levels of impact strength and very low levels of heat input. For the 409M and X6CrNiTi1811 high fatigue limit coupled with high impact strength corresponds to intermediate heat input. For the AISI 1020 and 1045 both fatigue limit and yield strength correspond to low heat input.

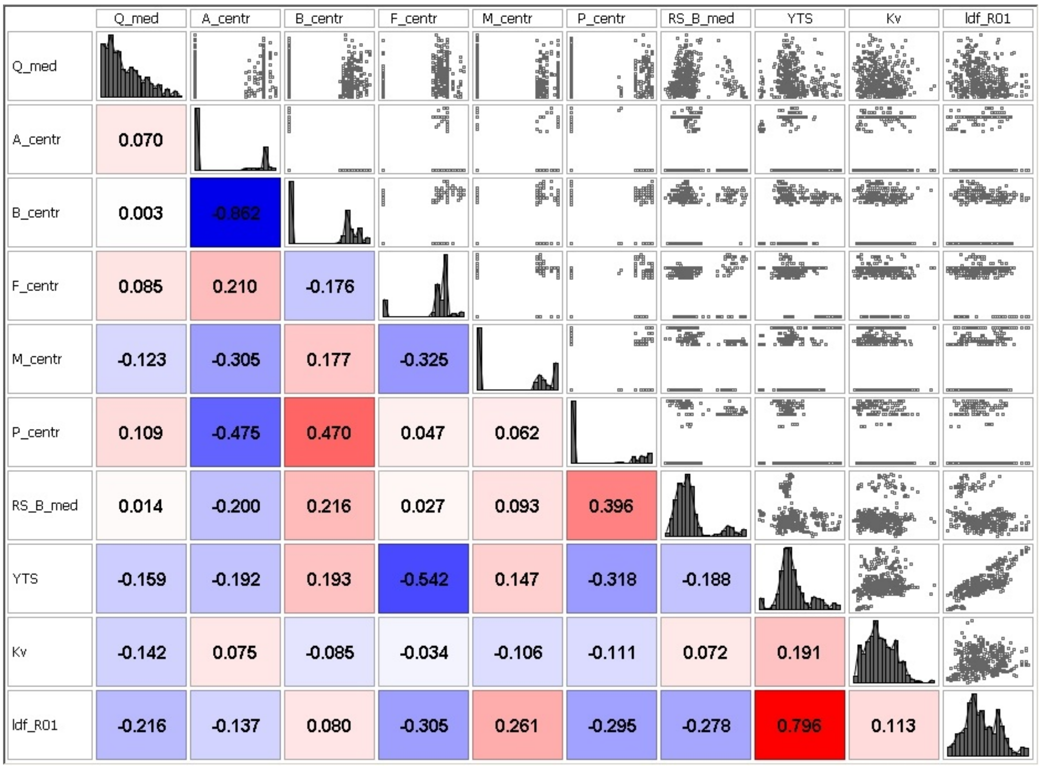


Figure 2: Matrix correlating all the input and output variables of the present study.

For X5CrNi1810 and Weldox1100E the highest values are in correspondence of low and intermediate heat input, For X6CrNiTi1811 to intermediate heat input. For X5CrNiMo1712, 409M, AISI4340 and HSLA100 they corresponds to low heat input. For AISI 1020 and 1045 both fatigue limit and impact strength increase with increasing residual stresses. For X5CrNi1810 and Weldox1100E both fatigue and impact strength are high in a broad range of residual stresses. For X5CrNiMo1712 the strength is maximum for intermediate residual stresses. For 409M and HSLA100 high impact and fatigue strength correspond to high residual stresses. For X6CrNiTi1811 the high impact strength and fatigue life correspond to low to intermediate residual stresses. For AISI 4340 both fatigue and impact strength are high for high to intermediate residual stresses; some sampling results are plotted in Fig. 3.

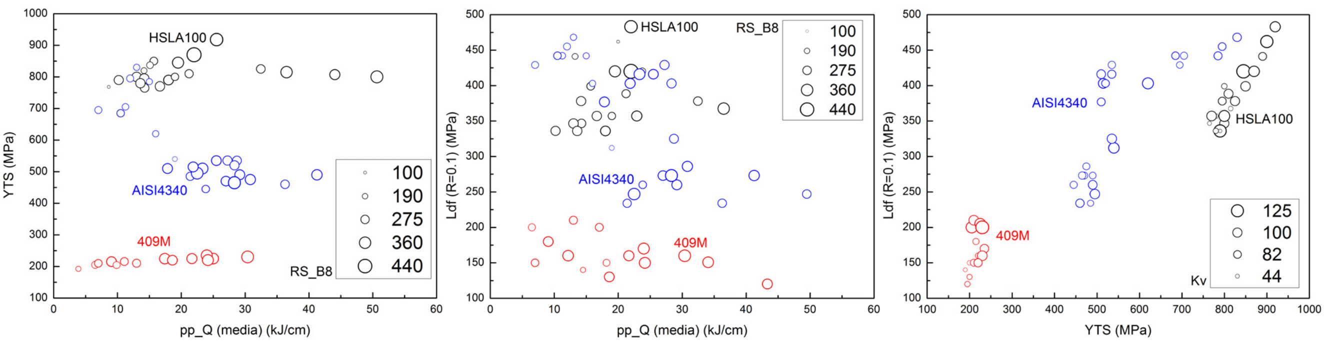


Figure 3: Mechanical properties of sampling welds.

A deep analysis has been performed on the phase transformations influencing mechanical properties; by taking into account fatigue limit and impact strength and fixing one condition it can be observed that: AISI 1020, 1045 and 409M welds show the best fatigue limit and impact strength for ferrite-martensite rich microstructure; X5CrNi1810, X5CrNiMo1712 and X6CrNiTi1811 show always austenite-ferrite microstructure; For the AISI 4340 the best fatigue life corresponds to martensite-ferrite microstructure while good fatigue life and high impact strength correspond to martensite-ferrite-austenite microstructure.

From the performed analysis a deep dependence from the heat input was underlined in the mechanical properties. In Fig. 4 sampling correlations between fatigue properties, impact strength and heat input are shown for different steel.

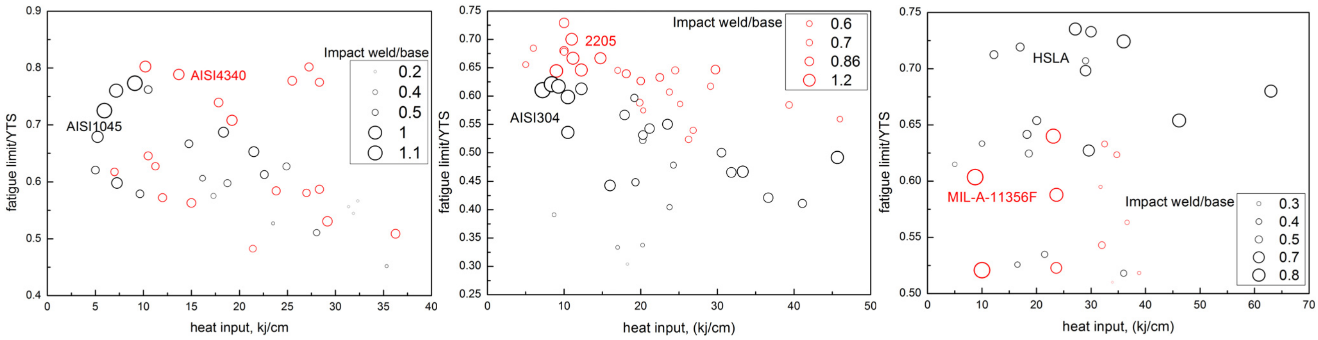


Figure 4: Fatigue properties vs. Heat input for different impact toughness for sampling welds.

For AISI1045 and AISI4340 high fatigue properties and high impact toughness are experienced for low heat input. AISI304 and Duplex steel 2205 follow the same behaviour. In the case of HSLA and MIL-A-11356F steel the best correlation between impact and fatigue strength are in correspondence of intermediate heat input. In such a way it was possible to identify the best processing conditions in order to obtain the best properties in terms of tensile, fatigue and impact properties of the studied welds.

## CONCLUSIONS

Through a multi-objective optimization tool it was possible to analyze the mechanical and microstructural optimal combination for different steel fusion welded. In particular, the fatigue and impact resistance of gas metal arc welded steel joints have been analyzed in a broad range of processing conditions. The optimal correlation between microstructure-fatigue-impact strength of many steels have been individuated and have been employed for a multi objective analyses performed through numerical procedure. All the properties have been demonstrated to be influenced strongly by heat input strongly related to microstructure modifications. All the obtained data have been employed to build a broad provisional database for industrial welding procedures.

## REFERENCES

[1] E. Taban, Journal of Mater. Sci., 43 (2008) 4309.
[2] P. Deb, K. D. Challenger, A.E. Therrienc, Metallurgical Trans., 18A (1987) 987.
[3] Chih-Chun Hsieh, Tao-Chih Chang, Dong-Yih Lin, Ming-Che Chen, Weite Wu, Metals and Mater. Int., 13 (2007) 411.
[4] V. Thomas Paul, S. Saroja, P. Hariharan, A. Rajadurai, M. Vijayalakshmi, Journal of Mater. Sci., 42 (2007) 5700.
[5] Woei-Shyan Lee, Fan-Tzung Tzeng, Chi-Feng Lin, Journal of Mater. Sci., 40 (2005) 4839.
[6] J. Gomez de Salazar, A. Soria, M. Barrena, Journal of Mater. Sci., 42 (2007) 4892.
[7] B. Arivazhagan, M. Kamaraj, Journal of Mater. Eng. And Perf., DOI: 10.1007/s11665-010-9757-3.
[8] S.P. Kumaresh Babu, S. Natarajan, Journal of Mater. Eng. And Perf., 16 (2007) 620.

## ACKNOWLEDGMENTS

The authors gratefully acknowledges Puglia Region Administration for the founding provided to the project STAR-EXD, code USUGVA1, "Intervento cofinanziato dall'U.E. – F.E.S.R. sul P.O. Regione Puglia 2007-2013, Asse I-Linea 1.1 - Azione1.1.2 Aiuti agli Investimenti in Ricerca per le PMI".

## TABLES NOMENCLATURE

| | |
|---|---|
| pp_n_p_TOT: | total number of passes; |
| pp_n_p: | number of pass identification; |
| pp_I: | welding current; |
| pp_speed: | welding speed; |
| pp_V: | welding voltage; |
| pp_Q: | welding input; |
| RS_Ax: | residual stresses at x position; |
| Hv_Ax: | microhardness at x position; |
| M_s_A: | martensite starting point; |
| M_f_A: | martensite ending point; |
| B_s_A: | bainite starting point; |
| B_f_A: | bainite ending point; |
| P_s_A: | perlite starting point; |
| P_f_A: | perlite ending point; |
| F_s_A: | ferrite starting point; |
| F_f_A: | ferrite ending point; |
| A_s_A: | austenite starting point; |
| A_f_A: | austenite ending point; |
| Ldf: | stress amplitude of infinite life. |