

Article

Process Monitoring in Friction Stir Welding Using Convolutional Neural Networks

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Supplementary Materials

The following are available online at www.mdpi.com/xxx/s1

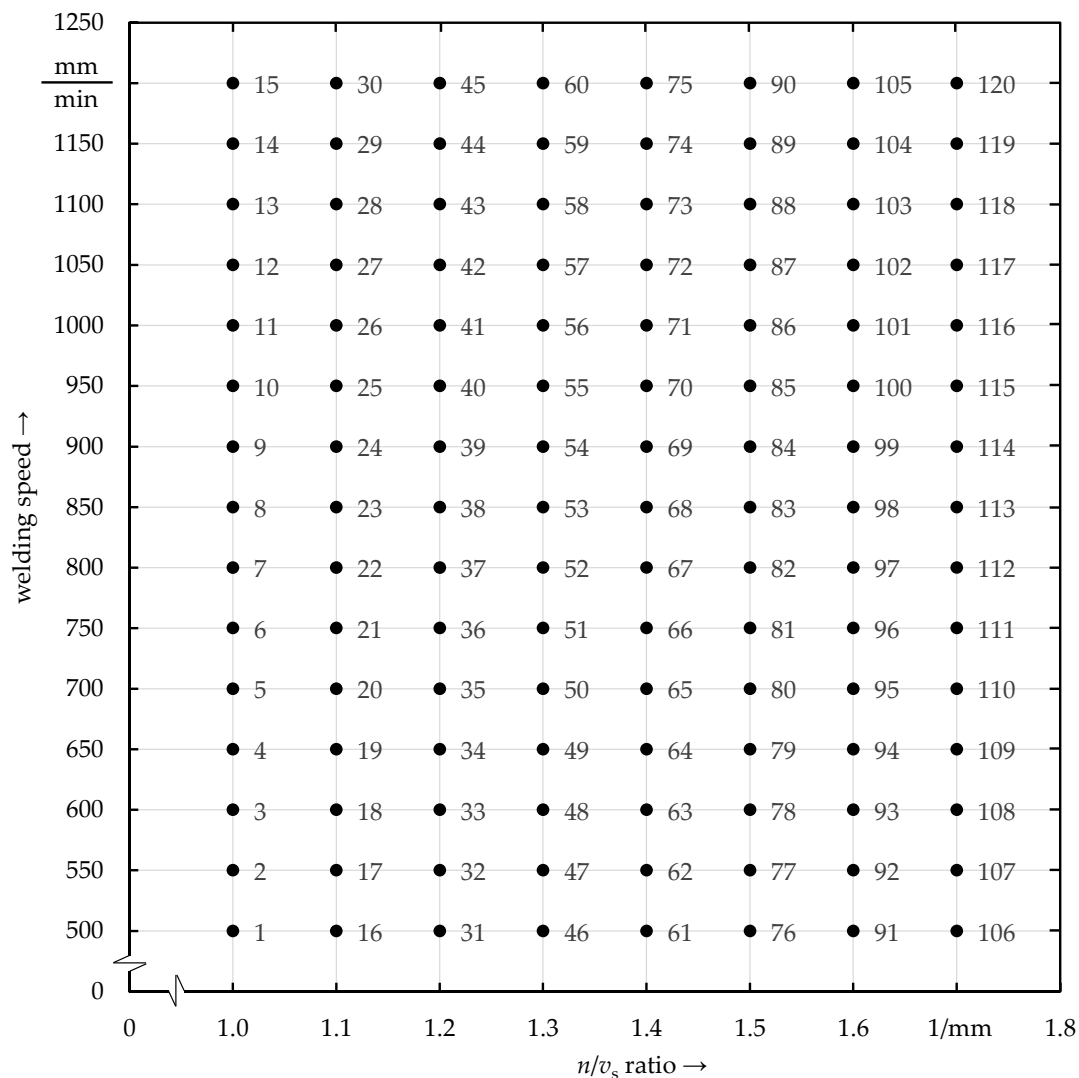


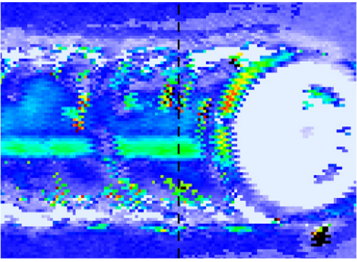
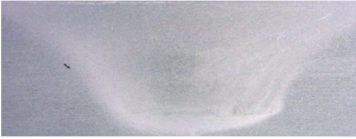
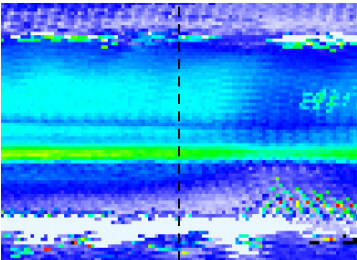
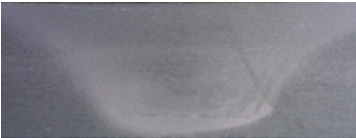
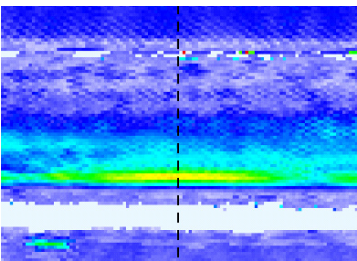

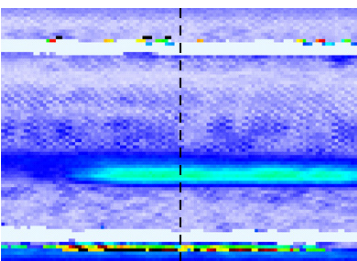
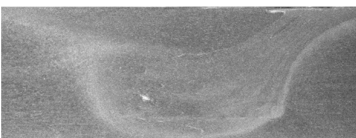
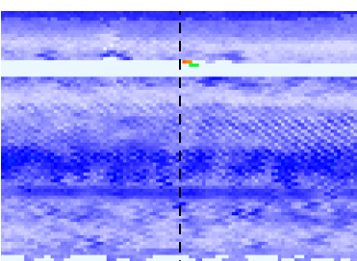
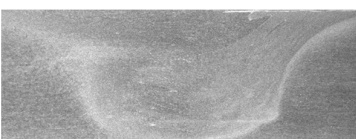
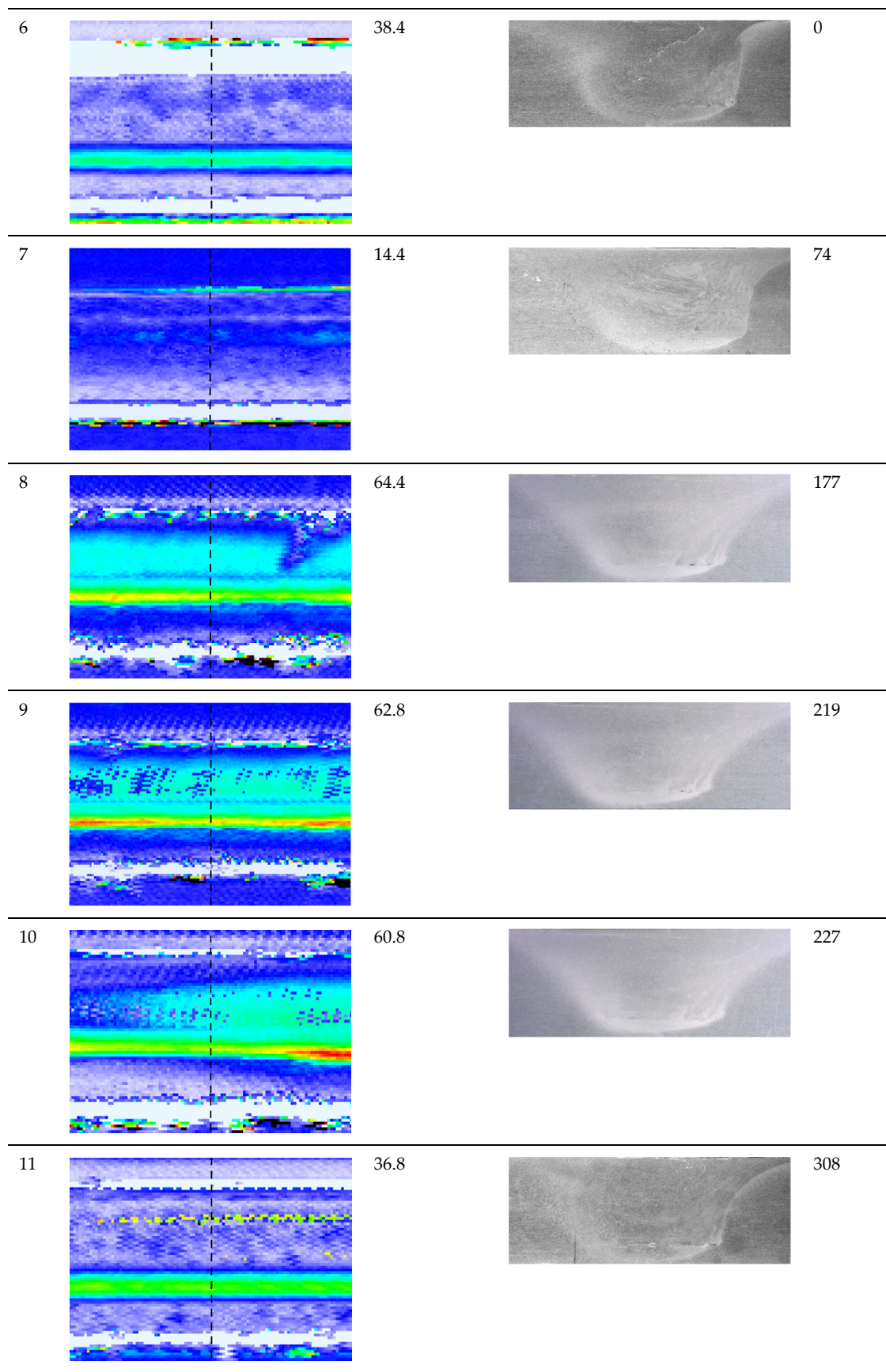
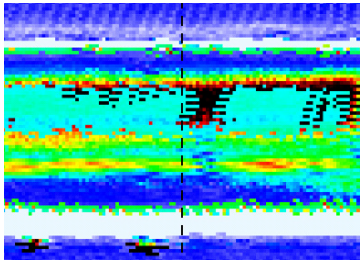

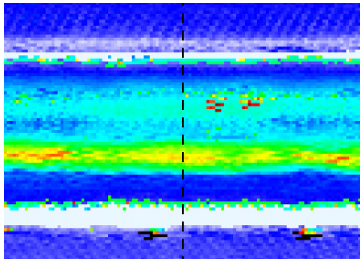

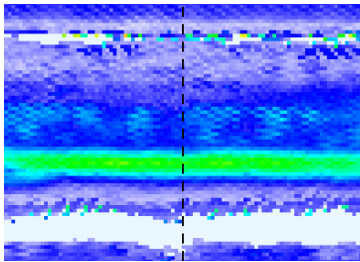
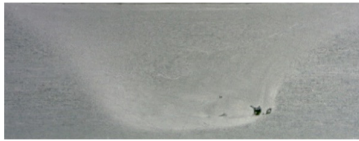
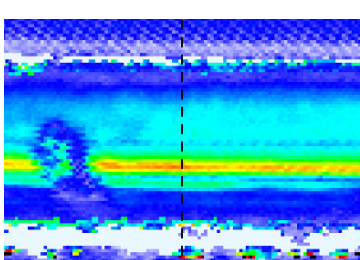

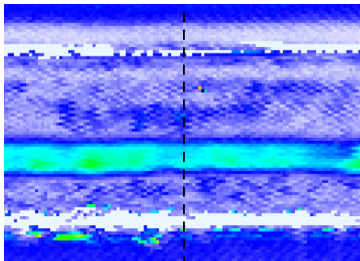
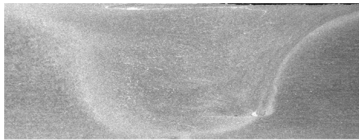
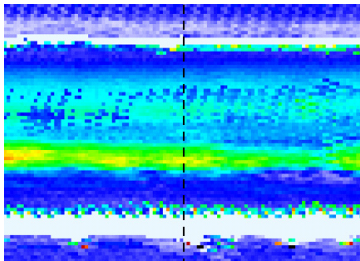



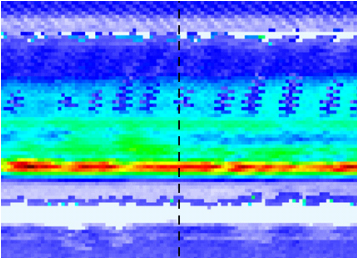

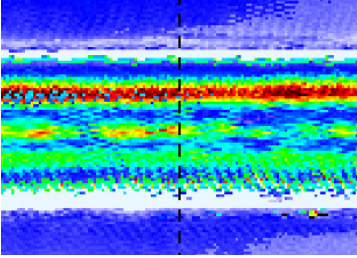
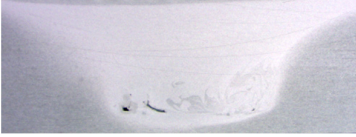
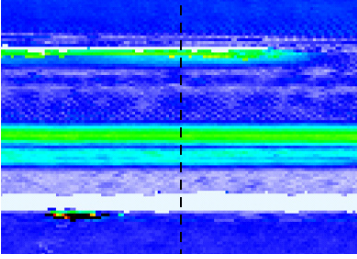
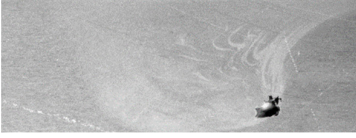
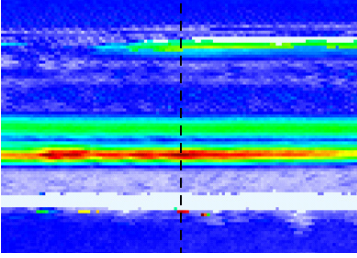
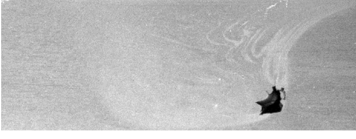
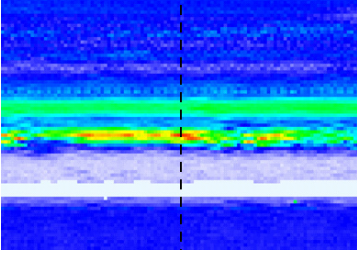
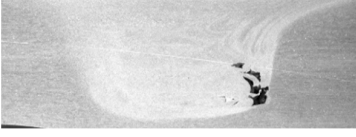
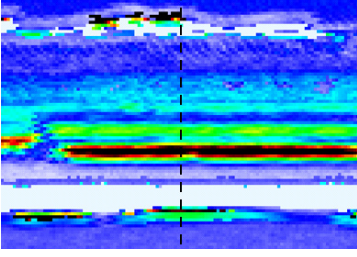

Figure S1. Full experimental plan with experiment numbers

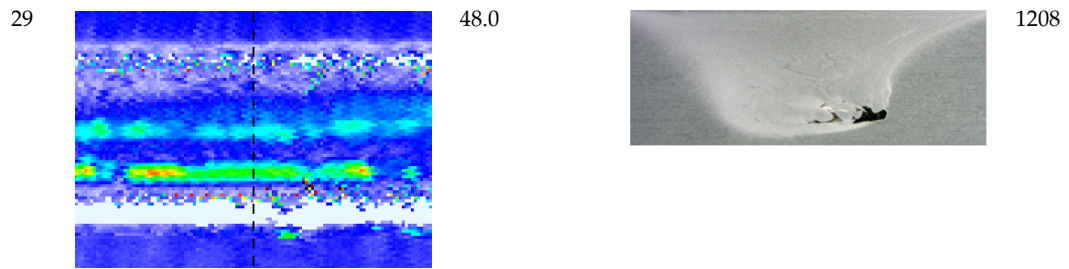
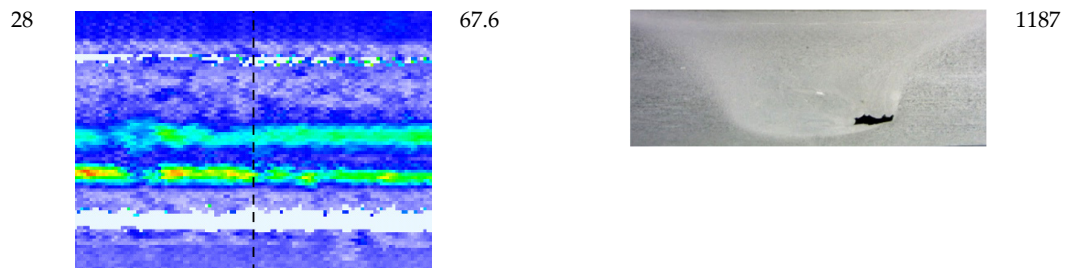
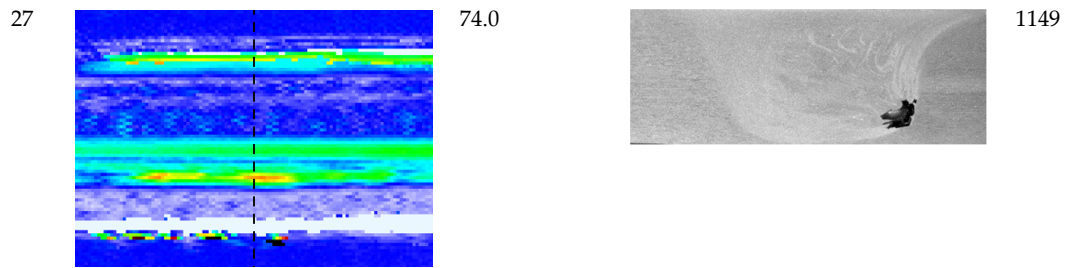
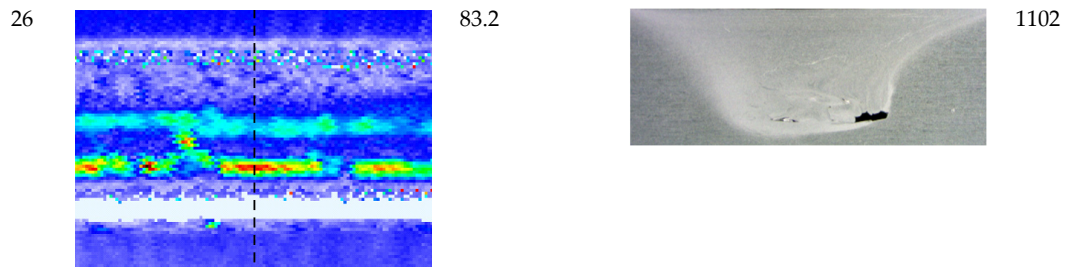
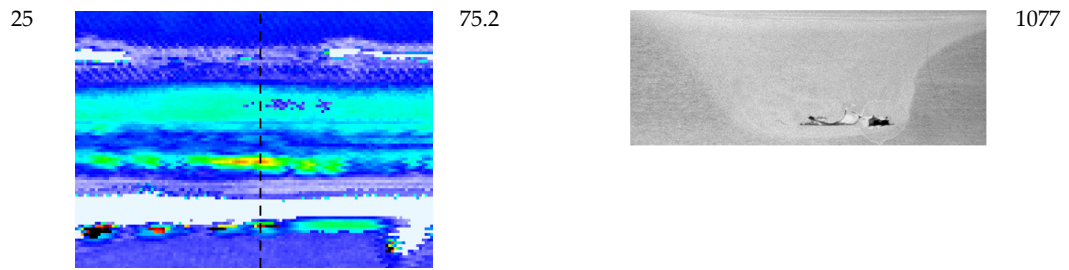
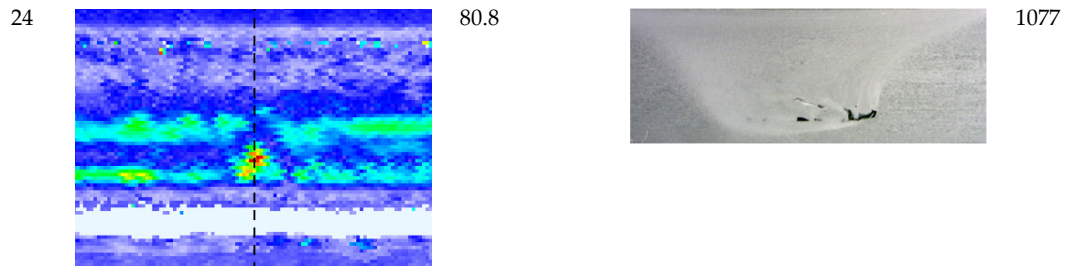
Table S1. Ultrasonic testing images and corresponding metallographic images (in the ultrasonic testing images, the advancing side is at the bottom part of the image. In the metallographic images, the advancing side is on the right part of the images)

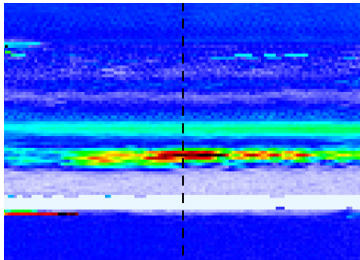
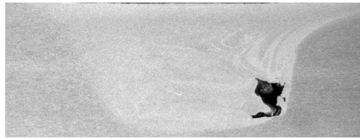
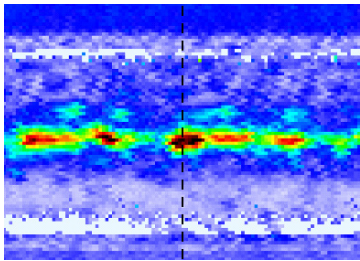
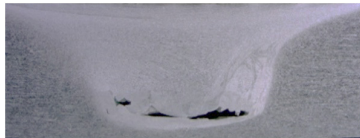
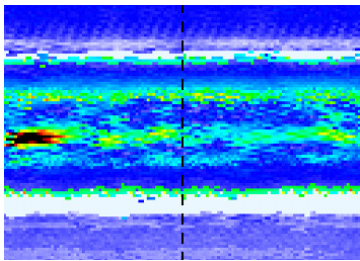
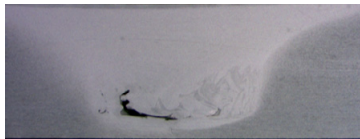
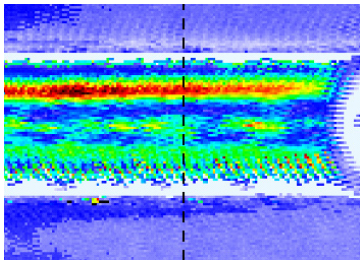

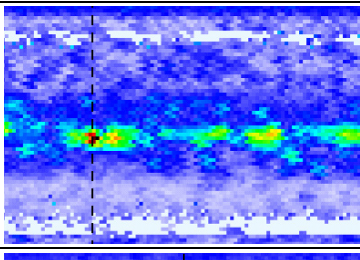
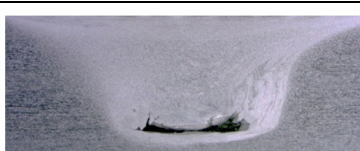
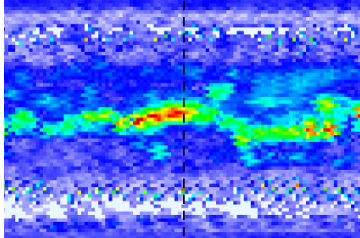
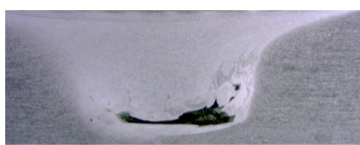
No.	Ultrasonic testing image 	Screen height in %	Metallographic image 	Cavity size in μm
1		45.6		0
2		54.0		0
3		68.8		0
4		35.2		0
5		11.6		0



12		67.6		313
13		68.4		349
14		44.0		366
15		76.0		373
16		32.8		388
17		67.2		416

18		83.6		569
19		89.2		620
20		51.6		866
21		82.0		959
22		80.8		963
23		102.0		986



30		97.6		1320
31		100.0		1795
32		68.4		2086
33		88.4		2670
34		71.6		3425
35		84.0		3430

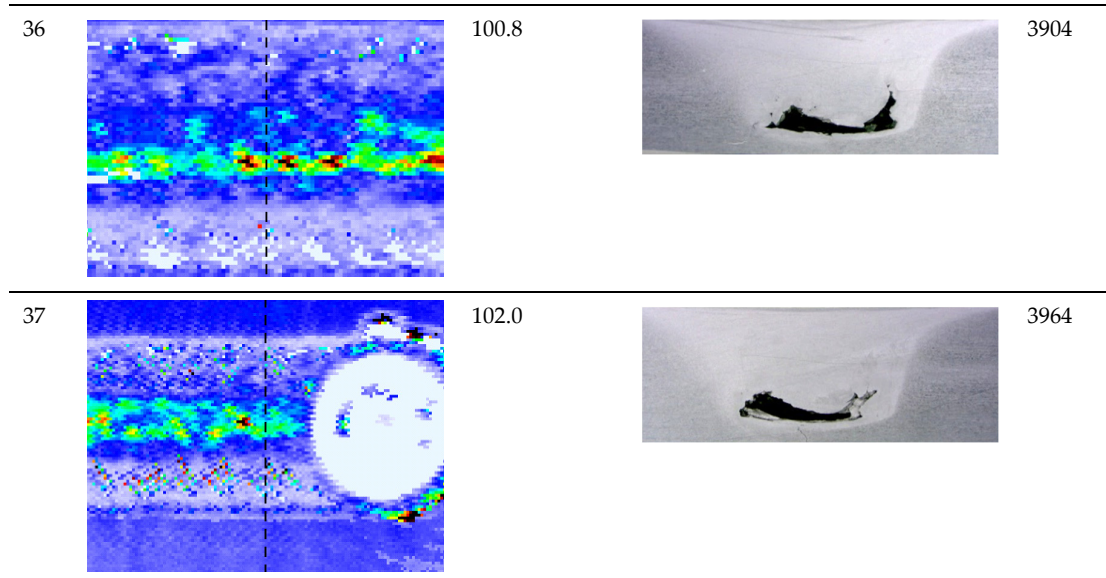


Table S2. Mean and root means square (RMS) values of the recorded process variables for all 120 performed welding experiments

Exp. no.	Process variable								
	a_x	a_y	a_z	F_x	F_y	F_z	M_z	T_P	T_S
Value	RMS	RMS	RMS	Mean	Mean	Mean	Mean	Mean	Mean
Unit	m/s ²	m/s ²	m/s ²	kN	N	kN	Nm	°C	°C
1	0.11	0.13	0.14	4.5	19	10.3	26.0	395	386
2	0.13	0.11	0.15	4.2	-104	9.7	25.1	405	396
3	0.08	0.09	0.12	3.7	-45	9.2	24.5	414	405
4	0.11	0.10	0.12	3.7	-255	9.2	23.6	421	410
5	0.50	0.44	0.60	3.5	-312	8.9	23.0	428	417
6	0.13	0.11	0.17	3.3	-396	8.7	22.4	433	422
7	0.97	0.82	0.58	3.1	-587	9.0	22.2	441	431
8	0.32	0.17	0.14	3.3	-324	8.5	21.1	441	431
9	0.94	0.60	0.77	2.8	-906	8.9	21.1	451	440
10	0.21	0.15	0.17	3.0	-685	8.6	20.4	450	441
11	1.10	0.86	0.97	2.7	-1061	9.0	20.6	461	452
12	0.20	0.16	0.15	2.7	-875	8.3	19.4	459	450
13	1.05	0.71	1.01	2.7	-1078	8.8	19.5	468	458
14	0.24	0.21	0.23	2.7	-1007	8.4	18.8	467	460
15	1.61	1.11	1.58	2.6	-1035	8.9	19.2	477	468
16	0.53	0.43	0.49	3.8	-167	9.6	25.1	408	399
17	0.09	0.09	0.13	3.5	-214	9.0	23.6	415	405
18	0.44	0.55	0.66	3.2	-281	8.8	23.3	425	416
19	0.40	0.40	0.40	3.0	-325	8.5	22.6	433	423

20	0.82	0.73	0.84	2.7	-545	8.5	22.2	438	429
21	0.22	0.16	0.15	2.5	-750	8.4	21.6	446	437
22	0.18	0.15	0.11	2.3	-1067	8.7	21.7	456	447
23	0.40	0.37	0.36	2.3	-855	8.4	20.5	457	448
24	0.14	0.18	0.14	2.2	-1048	8.8	20.9	469	459
25	0.18	0.16	0.16	2.1	-839	8.5	19.9	469	459
26	0.17	0.16	0.18	2.2	-1105	8.6	19.8	478	468
27	0.21	0.17	0.16	2.3	-1023	8.1	18.4	472	462
28	0.20	0.16	0.21	2.3	-1118	8.5	18.8	484	475
29	0.31	0.31	0.24	2.4	-868	8.1	17.5	475	469
30	0.26	0.20	0.23	2.3	-1176	8.5	18.1	493	483
31	0.14	0.13	0.14	3.1	-213	10.1	25.9	429	421
32	0.11	0.11	0.16	2.7	-321	8.4	23.5	430	420
33	0.10	0.12	0.13	2.2	-714	9.6	24.5	447	440
34	0.15	0.16	0.15	2.5	-582	7.9	21.3	441	430
35	0.17	0.16	0.13	2.0	-738	9.3	22.9	461	454
36	0.20	0.14	0.17	2.1	-641	7.9	20.4	454	445
37	0.15	0.13	0.11	1.9	-716	9.5	21.7	476	469
38	0.37	0.39	0.38	1.8	-851	8.1	19.9	471	461
39	0.17	0.17	0.22	1.9	-763	9.5	20.6	488	480
40	0.19	0.16	0.21	2.0	-956	8.2	18.5	479	468
41	0.16	0.15	0.19	1.9	-794	9.5	19.7	499	492
42	0.26	0.24	0.17	2.0	-819	7.8	17.1	479	470
43	0.19	0.19	0.16	1.9	-736	9.5	19.3	508	502
44	0.22	0.20	0.18	2.0	-815	9.5	18.3	505	493
45	0.21	0.21	0.20	1.9	-688	9.5	18.6	516	510
46	0.10	0.15	0.16	2.5	-496	8.1	23.4	434	426
47	0.12	0.12	0.13	2.4	-381	7.7	21.8	436	426
48	0.19	0.18	0.17	1.9	-813	7.9	22.1	452	444
49	0.20	0.14	0.16	1.9	-789	7.7	20.7	454	444
50	0.16	0.18	0.17	1.7	-840	7.8	20.4	465	456
51	0.14	0.15	0.19	1.8	-857	7.5	19.2	465	453
52	0.17	0.18	0.25	1.7	-878	8.2	19.5	481	471
53	0.18	0.15	0.19	1.8	-899	7.4	17.9	473	462
54	0.21	0.19	0.24	1.8	-829	7.7	18.2	485	477
55	0.39	0.36	0.38	1.8	-858	7.7	17.0	483	472
56	0.20	0.19	0.18	1.7	-904	7.8	17.3	496	486
57	0.26	0.23	0.25	1.7	-886	7.6	16.2	491	476
58	0.26	0.25	0.26	1.8	-837	8.0	16.6	505	494
59	0.43	0.35	0.27	2.0	-714	7.6	15.6	491	485

60	0.36	0.33	0.30	1.9	-805	8.0	16.1	514	500
61	0.14	0.11	0.09	2.2	-773	8.4	22.4	448	438
62	0.14	0.20	0.14	2.1	-908	8.1	21.4	455	445
63	0.12	0.20	0.14	1.9	-872	8.6	21.2	467	457
64	0.15	0.24	0.13	2.0	-872	8.6	20.1	474	462
65	0.18	0.14	0.12	2.1	-933	8.1	18.6	476	460
66	0.28	0.15	0.14	2.3	-1035	7.1	16.3	464	446
67	0.22	0.16	0.16	2.5	-1064	7.2	15.8	470	454
68	0.22	0.15	0.19	2.4	-1111	7.4	16.0	480	464
69	0.25	0.19	0.17	2.5	-1099	7.6	15.5	485	470
70	0.31	0.21	0.18	2.7	-1148	7.3	14.8	484	471
71	0.35	0.24	0.18	2.6	-1111	7.3	14.7	489	476
72	0.40	0.28	0.19	2.7	-1136	7.3	14.1	490	478
73	0.45	0.31	0.23	2.7	-1116	7.3	13.9	494	482
74	0.46	0.36	0.26	2.6	-1150	7.1	13.4	495	482
75	0.52	0.40	0.34	2.7	-1147	7.2	13.2	497	485
76	0.12	0.17	0.14	2.4	-832	7.6	19.7	447	433
77	0.20	0.17	0.18	1.8	-854	7.9	20.1	464	452
78	0.42	0.36	0.25	1.9	-886	7.9	19.1	470	457
79	0.15	0.14	0.15	1.9	-883	7.9	18.3	476	462
80	0.20	0.14	0.25	2.1	-935	7.4	16.8	475	457
81	0.17	0.14	0.23	2.0	-919	8.0	17.1	489	473
82	0.24	0.15	0.12	2.1	-938	8.0	16.5	493	477
83	0.25	0.20	0.20	2.3	-981	7.4	15.1	488	473
84	0.28	0.21	0.17	2.2	-984	7.9	15.2	499	483
85	0.38	0.27	0.21	2.3	-969	7.4	14.5	495	481
86	0.43	0.35	0.19	2.4	-993	7.4	14.0	499	486
87	0.47	0.39	0.30	2.4	-962	7.4	13.8	504	490
88	0.47	0.34	0.32	2.4	-1002	7.5	13.5	511	496
89	0.48	0.39	0.33	2.3	-928	7.4	13.3	516	499
90	0.67	0.37	0.44	2.3	-917	7.4	13.1	521	502
91	0.21	0.15	0.12	2.3	-849	6.7	17.8	447	430
92	0.16	0.25	0.12	2.4	-1017	6.3	16.3	446	428
93	0.12	0.14	0.13	2.4	-1026	6.4	15.7	454	438
94	0.17	0.15	0.14	2.4	-992	6.4	15.2	460	446
95	0.18	0.18	0.16	2.4	-1051	6.4	14.7	465	451
96	0.24	0.20	0.15	2.3	-1065	6.3	14.3	469	457
97	0.29	0.27	0.14	2.4	-1083	6.3	13.8	469	460
98	0.42	0.34	0.17	2.4	-1111	6.2	13.4	473	465
99	0.48	0.38	0.17	2.3	-1094	6.2	13.2	476	470

100	0.51	0.42	0.27	2.3	-1116	6.4	13.0	484	477
101	0.52	0.48	0.28	2.2	-1079	6.3	12.5	484	480
102	0.53	0.42	0.38	2.2	-1073	6.6	12.4	493	486
103	0.64	0.49	0.39	2.1	-1094	6.6	12.3	500	491
104	1.07	0.49	0.48	2.2	-1121	6.2	11.6	495	489
105	1.70	0.78	0.37	2.3	-1223	6.2	11.4	498	489
106	0.17	0.16	0.13	2.3	-904	6.4	16.6	448	430
107	0.19	0.22	0.12	2.1	-993	6.3	16.1	453	437
108	0.15	0.16	0.12	2.2	-983	6.2	15.2	457	441
109	0.20	0.20	0.17	2.2	-1036	6.1	14.6	459	446
110	0.23	0.23	0.15	2.2	-1088	6.0	14.0	462	452
111	0.26	0.26	0.17	2.2	-1082	6.1	13.7	467	458
112	0.38	0.31	0.20	2.3	-1112	6.0	13.2	470	462
113	0.45	0.39	0.17	2.3	-1163	5.9	12.2	470	464
114	0.47	0.42	0.25	2.2	-1092	5.9	12.1	477	473
115	0.53	0.48	0.36	2.1	-1070	6.0	11.9	481	476
116	0.64	0.49	0.32	2.1	-1100	6.0	11.6	486	481
117	0.73	0.48	0.39	2.1	-1104	6.0	11.4	491	486
118	1.49	0.70	0.41	2.1	-1129	6.1	16.5	494	489
119	2.20	1.03	0.36	2.0	-1044	6.4	11.4	511	498
120	2.53	1.09	0.29	1.8	-1013	6.5	16.6	522	506

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