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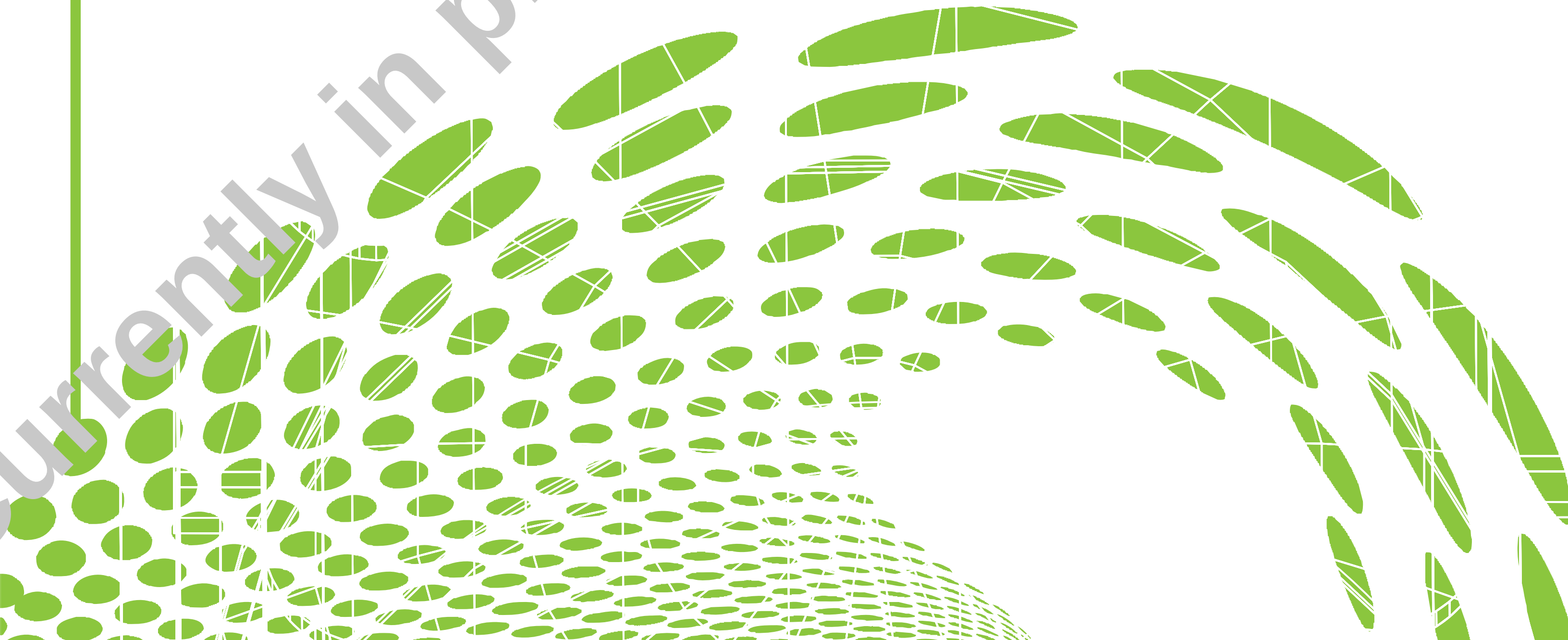
STP-PT-088

EFFECT OF COOLING RATE ON THE MICROSTRUCTURE AND PROPERTIES OF DUPLEX STAINLESS STEEL WELDS



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EFFECT OF COOLING RATE ON THE MICROSTRUCTURE AND PROPERTIES OF DUPLEX STAINLESS STEEL WELDS

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FOREWORD

The purpose of this project is to evaluate the cooling rate effects on the toughness properties of the heat-affected zone of different duplex stainless steel alloy welds. The heat-affected zone austenite and ferrite microstructure phase balance is controlled by the weld cooling rate and could result in a heat-affected zone microstructure with lower toughness than the unaffected base material. Kiefner and Associates, Inc. was the project coordinator and contracted the metallurgical testing and analysis to The Ohio State University.

Both Kiefner and Associates, Inc. and The Ohio State University would like to acknowledge ASME for funding this entire project as well as Outokumpu, ATI Allegheny Ludlum, and Rolled Alloys for providing the duplex stainless steel materials that were evaluated during the project.

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1 INTRODUCTION

Duplex stainless steels are thermo-mechanically processed in order to produce microstructures that contain an equal balance of ferrite and austenite. The balanced microstructure affords duplex stainless steels the mechanical and corrosion properties that make them desirable for a wide range of applications. The duplex stainless steels are generally gathered into one of four alloy groups: lean duplex, duplex, super duplex and hyper duplex. These alloy groups are defined primarily on the basis of corrosion resistance, specifically the Pitting Resistance Equivalent Number (PRE_N).

Section IX of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) is an internationally recognized weld qualification code. Section IX of the BPVC (Section IX) categorizes base materials into P-numbers which are dependent on the alloy type and composition. Section IX further separates ferrous materials into Group numbers which differentiate similar alloys by the material's toughness properties. Section IX considers the four duplex stainless steel categories to be the same P-number and Group number which would imply that the different duplex stainless steels are comparable when it comes to chemical composition, weldability and mechanical properties including toughness.

Duplex stainless steel base metals achieve the balanced microstructure and proper phase balance through chemical composition controls, heat treatment and cooling rate control. Use of an annealing temperature where equal proportions of ferrite and austenite are formed followed by rapid cooling to maintain that phase balance is used to develop microstructures with a nominal 50/50 balance of ferrite and austenite. Since welding creates a range of thermal cycles with different peak temperatures and cooling rates an unequal phase balance may exist in the different heat-affected zone (HAZ) regions. It is known that high ferrite levels in the HAZ microstructure can result in a reduction in the toughness and corrosion properties of the HAZ relative to the base metal. Unlike the weld metal where ferrite to austenite balance can be controlled by proper filler metal selection (composition control) the ferrite to austenite balance in the HAZ is primarily a function of cooling rate. The cooling rates in the HAZ are a function of the welding heat input, material thickness, and preheat and interpass temperatures.

The objective of this project was to determine the effect of variations in cooling rate on the microstructure and toughness of the HAZ of duplex stainless steel alloys 2003, 2101, 2205, 2304, 2507, and Zeron 100. The variation in cooling rate was achieved using both thermal simulation and heat input control in actual welds.

2 LITERATURE REVIEW

A literature search was performed with the goal of gathering information pertaining to duplex stainless steels. The literature search was limited to relevant papers that covered one of two topics. The first topic was the relationship between cooling rates, duplex stainless steel microstructures, and the corresponding toughness properties of the materials. This review included data relevant to base material cooling rates to simulate the HAZ of welds and did not include weld metal cooling rate data. The second topic included a compilation of general industry duplex stainless steels welding practices.

2.1 Relationship of Cooling Rate to Toughness Properties in Duplex Stainless Steels

This portion of the review was intended to quantify the effect of different cooling rates on the toughness properties of different duplex stainless steels. The relevant data consisted of small samples of the duplex stainless steels heated and cooled to simulate the thermal cycle experienced by the weld HAZ. The simulated conditions consisted of rapidly heating the sample to a peak temperature (typically between 1300 C and 1400 C depending on the alloy), holding the sample at the peak temperature for a set time (zero to ten seconds) and then cooling the sample at a specified cooling rate. The small samples that were subjected to the thermal cycle were then machined into Charpy V-Notch (CVN) samples and tested to determine the material toughness.

The previous research was difficult to directly compare because of three primary factors. First, the reported cooling conditions varied among different investigators and included cooling times from 1200 C (t_{12-8}) to 800 C (t_{12-8}), 800 C (t_{12-8}) to 500 C (t_{8-5}), or an arbitrary fixed cooling rate from peak temperature. There was no clear correlation among the three different cooling conditions. The t_{12-8} is most appropriate for duplex stainless steels since that is the temperature range over which the ferrite-to-austenite transformation occurs. The t_{8-5} is appropriate for carbon and alloy steels, but there are no phase transformations in the duplex stainless steels in this temperature range.

The second factor was the variation in peak temperature and hold time at the peak temperature. These parameters were shown to affect the resulting duplex stainless steel microstructures and as such resulted in a difference in the CVN toughness of the same material. Higher peak temperatures and longer holding times result in more extensive ferrite formation and excessive grain growth, both of which negatively affect toughness.

The third factor was the variation in the CVN sample size ranging from near half size CVN samples (4.5 mm by 10 mm) to full size CVN samples (10 mm by 10 mm). The reported results were most commonly in terms of the actual impact energy for the sample sizes tested and, in many cases, were not converted to full size equivalent values. The conversion to full size specimens may increase the scatter in the data.

The data included in the review pertained primarily to six different duplex stainless steel alloys: Grade 2377 (also known as Grade 2205), 25 Cr duplex stainless steel with 0.17% nitrogen, Ferralium 255, Uranus 52N, SAF 2205 and SAF 2507. In several cases, the data for a single duplex stainless steel alloy consisted of several different chemical compositions from multiple sources. The duplex stainless steels evaluated had a PRE_N[1] of between 32.8 and 42.3. Materials with PRE_N within this range are typically considered to be duplex or super duplex stainless steels.[1] The majority of the published research centered on alloys SAF 2205 and SAF 2507 which represent the duplex stainless steels that have been most widely adopted for structural applications.

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[1] $PRE_N = Cr + 3.3(Mo + 0.5W) + 16N$

Cao and Hertzman studied the effects of cooling rate on two different duplex stainless steel alloys of Grade 2377 and one 25 Cr duplex stainless steel using thermal simulation to create HAZ microstructures.[2] The PRE_N range for these duplex stainless steels was between 34.0 and 37.7. The samples were subjected to a peak temperature of 1350 C, three different peak temperature exposure times (zero, five, and ten seconds) and three different cooling rates (160 C/sec, 300 C/sec, and 430 C/sec). All the samples were machined into half size CVN samples (5 mm by 10 mm) and tested at room temperature. The results showed that, regardless of the duplex stainless steel tested, the slower cooling rate resulted in higher impact energy at room temperature which was attributed to the increase in austenite content; however, there was no analysis of the microstructure included in the report.

Cao and Hertzman also performed limited research on samples that were subjected to a second thermal cycle to simulate the reheating effect from a subsequent weld pass on the HAZ of the original pass in a multipass weld. The samples were subjected to an original thermal cycle including heating the sample to 1350 C, holding for 5 seconds and then cooling to room temperature at either 160 C/sec or 430 C/sec followed by a second thermal cycle with a peak temperature of either 1050, 900, 800, or 700 C and allowed to cool after no hold time at a cooling rate much slower than the original thermal cycle. The results of the reheating study showed toughness properties could be recovered as a result of exposing the original HAZ to a second heating cycle. The extent of the recovery was related to the peak temperature of the second thermal cycle. The toughness improvement was credited to the formation of additional austenite during the reheating cycle. Menon *et al*. studied two different stainless steel alloys of Ferralium 255 which both had a PRE_N of 37.9.[3]

The samples were subjected to a peak temperature of 1300 C, two different peak temperature exposure times (1 second and 10 seconds) and four different cooling rates (2 C/sec, 20 C/sec, 50 C/sec, and 75 C/sec). The range of cooling rates were considered representative of the range of cooling rates that would be experienced in the HAZ of low heat input welds deposited using the shielded metal arc welding (SMAW) process and a high heat input weld deposited using the submerged arc welding (SAW) process. The resulting Ferrite Number (FN) ranged from 91 for a cooling rate of 2 C/sec up to 112 C/sec for a cooling rate of 75 C/sec. All the samples were full sized CVN samples (10 x 10 mm) and tested at a six different test temperatures (-100, -60 C, -40 C, -20 C, 20 C, and 100 C). Both duplex stainless steels exhibited a similar decrease in toughness as the cooling rates increased for samples tested at the same test temperature. The study related the toughness over the range of cooling rates as a function of the ferrite to austenite balance, prior grain size and degree of precipitation. The results showed that the faster cooling rates resulted in higher ferrite content and smaller grains.

Lippold *et al.* evaluated the microstructure and toughness of the HAZ of Uranus 52N which had a PRE_N of 41.3.[4] The samples were subjected to a peak temperature of 1350 C, a peak temperature exposure time of 1 second and two different cooling rates (20 C/sec and 50 C/sec). The full size CVN samples (10 mm by 10 mm) were tested at 20 C. The results of the toughness tests did not show a large variation over the relative small range of cooling rates evaluated. The authors suggested that this response would be expected given the small variation between the two microstructures which were 78 FN and 85 FN for the corresponding cooling rates of 20 C/sec and 50 C/sec, respectively. The toughness values of the simulated HAZs (141 Joules and 159 Joules) were much less than the recorded toughness of the unaffected base metal which was recorded to be 243 Joules.

Two papers compared cooling rates to toughness data relevant to SAF 2205.[3,5] The two SAF 2205 duplex stainless steels tested had a PRE_N of 32.8 and 33.5. The samples were subjected to a peak temperature of 1300 C or 1370 C and, where reported, peak temperature exposure times were either 1 second or 10 seconds. The cooling conditions were reported as $t_{12\text{-}8}$, $t_{8\text{-}5}$ or actual cooling rate. The CVN sample sizes were either full size samples (10 mm by 10 mm) or near two-thirds size samples (6 mm by 10 mm). The range of eight testing temperatures was from -110 C to 20 C.

Menon *et al.* reported no significant difference in transition temperature of SAF 2205 between the two different cooling rates of 20 C/sec and 50 C/sec at the test temperatures evaluated.[3] These cooling rates resulted in a HAZ microstructure with 97 and 104 FN, respectively. The toughness was found to be a function of ferrite to austenite balance and prior ferrite grain size. In agreement with Menon *et al.*, Kivineva *et al.* showed that the highest cooling rates resulted in the lowest toughness values at all test temperatures.[5] Kivineva *et al*. suggested, based on their results, that 30 seconds was an optimum t_{12-8} for SAF 2205 which represents a cooling rate of 13.3 C/sec.

Three papers discussed the cooling rate effect on SAF 2507.[4,5,6] The duplex stainless steels evaluated had a range of PRE_N from 40.8 to 42.3. The samples were subjected to a peak temperature between of 1350 C and 1400 C and, where reported, the peak temperature exposure time was 1 second. The cooling conditions were reported as t_{12-8}, t_{8-5}, or actual cooling rate. The CVN samples sizes were either near two-thirds size samples (6 mm by 10 mm) or near half size samples (4.5 mm by 10 mm). There was a large range of test temperatures from -196 C to 20 C.

For the SAF 2507 duplex stainless steels, two papers showed that the t_{12-8} did not have a significant effect on the resulting toughness.[4,6] Kivineva *et al.* showed that the highest cooling rates resulted in the lowest toughness values at all test temperatures and the metallurgical analysis of the highest cooling rate samples showed the highest ferrite content and some chromium nitride precipitation in the ferrite. Slower cooling rates resulted in poorer toughness at low test temperatures but the toughness values increased to be comparable to base metal toughness values at higher test temperatures. The toughness reduction at the lower test temperatures for the slower cooling rate samples was related to the larger grain size present in the slowly cooled samples. Kivineva *et al.* proposed that 15 seconds was an optimum t_{12-8} for SAF 2205 which represents a cooling rate of 26.7 C/sec.

The data reported from the cooling rate effect on toughness portion of the literature review are summarized in Table 2-1 through Table 2-3. Table 2-1 provides the chemical composition of the different duplex stainless steels organized by increasing PRE_N.

Table 2-2 lists the thermal simulation conditions that were used to simulate the HAZ microstructure. The metallurgical analysis of the simulated HAZ microstructures is included in Table 2-3.

Table 2-1: Duplex Stainless Steel Chemical Compositions from Previous Research

Duplex Stainless Steel		Chemistry										
Alloy	**Thickness**	**Cr**	**Ni**	**Mo**	**Mn**	**Si**	**Cu**	**C**	**N**	**S**	**P**	**PRE$_N$**
SAF 2205	10 mm	21.75	5.82	2.73	1.74	0.48	-	0.019	0.13	0.002	0.021	32.8
	NR	22.12	5.73	2.8	1.78	0.2	-	0.022	0.13	0.002	0.028	33.4
	6 mm	22.4	5.6	2.9	1.49	0.48	0.23	0.019	0.155	0.001	0.021	33.5
22Cr12N	5 mm	22.01	5.63	3.05	1.51	0.42	-	0.024	0.12	0.001	0.024	34.0
22Cr18N	5 mm	22.03	5.71	3.16	1.5	0.4	-	0.021	0.18	0.001	0.024	35.3
25Cr17N	5 mm	25.1	5.8	3	1.87	0.45	-	0.026	0.17	0.003	0.01	37.7
Ferralium 255	10 mm	24.9	5.39	3.13	1.05	0.51	1.72	0.027	0.17	0.001	0.023	37.9
SAF 2507	4.5 mm	24.6	6.9	3.8	0.31	0.3	0.15	0.024	0.227	0.002	0.02	40.8
Uranus 52N	NR	25.19	6.37	3.67	1.18	0.25	-	0.018	0.25	0.001	0.018	41.3
SAF 2507	NR	24.7	7.1	3.82	0.62	0.26	-	0.06	0.28	0.005	0.023	41.8
	NR	25.4	6.7	3.8	-	-	-	-	0.27	-	-	42.3

NR = None Recorded

Table 2-2: Duplex Stainless Steel Thermal Simulation Conditions from Previous Research

Duplex Stainless Steel			Thermal Simulation Conditions				
Alloy	**Thickness, mm**	**PRE$_N$**	**Peak Temperature, C**	**Hold Time, sec**	**t_{12-8}, sec**	**t_{8-5}, sec**	**Cooling Rate, C/sec**
SAF 2205	10	32.8	1300	1 and 10			2
				1 and 10			20
				1 and 10			50
				1 and 10			75
SAF 2205	NR	33.4	1300	1			2
							20
							50
							75
SAF 2205	6	33.5	1370	NR	93	256	
					23	64	
					6.4	16	
					4.15	9	
22Cr12N	5	34.0	1350	0, 5, and 10			160
				0, 5, and 10			300
				0, 5, and 10			430
22Cr18N	5	35.3	1350	0, 5, and 10			160
				0, 5, and 10			300
				0, 5, and 10			430
25Cr17N	5	37.7	1350	0, 5, and 10			160
				0, 5, and 10			300
				0, 5, and 10			430
Ferralium 255	10	37.9	1300	1			2
				1 and 10			20
				1 and 10			50
				1 and 10			75
SAF 2507	4.5	40.8	1355	NR	93	256	
					23	64	
					6.4	16	
					2.8	6	
Uranus 52N	NR	41.3	1350	1			20
							50
SAF 2507	NR	41.8	1350	1			20
							50
SAF 2507	NR	42.3	1400	NR	114		
					6		

NR = None Recorded