DUPLEX STAINLESS STEELS

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This paper examines the properties, metallurgy and foundry performance of steels named for their characteristic two-phased microstructures. These alloys have developed into an important class of engineering materials with excellent strength, toughness, corrosion resistance, weldability and castability. Popular in Europe since the late 1950's, duplex stainless steel usage is now increasing in North America. Examined are the benefits of various remelt ingot production techniques, compositional balance for optimum properties and remelt considerations for investment casters. Also discussed are the important aspects of proper post-cast processing including the cleaning, heat treatment, machining and welding of duplex stainless steel castings.

INTRODUCTION

Stainless steels can be classed by room temperature microstructure- ferritic, austenitic, martensitic, precipitation-hardening or duplex. All stainless steels are iron based alloys with sufficient chromium added to provide a passive chromium oxide layer which resists further corrosive attack. The minimum amount of chromium which will provide this passivation is about 12%. The cast duplex stainless steels possess microstructures at room temperature which are composed of a mixture of ferrite and austenite, each of which contain chromium in excess of 12%, with overall compositions intermediate to the ferritic and austenitic grades.

Both wrought and cast duplex stainless steels are used in large quantities for components of exhaust gas scrubbers and pulp digesters, oil and gas hardware, heat exchangers, pumps, valves, fittings, boat propellers and other marine hardware. The alloys are best suited for designs which capitalize on the strength advantage they posses over conventional austenitic grades.

COMPOSITIONS

Listed in table #1 are compositions of several duplex and austenitic stainless steels. While dozens of duplex compositions are commercially available, those listed in table #1 are representative grades and can be found in ASTM A 890. Duplex stainless steels have evolved over time and are now categorized as being 1st or 2nd generation. The distinction is made based on the intentional addition of nitrogen. 1st generation alloys rely primarily on Cr and Ni balance alone for the development of the two-phase microstructure. 2nd generation alloys contain 0.1-0.4% nitrogen with several important benefits.

PROPERTIES

A most notable feature of the duplex stainless steels is their outstanding strength compared to both austenitic and ferritic grades. Table #2 compares the ultimate tensile, yield strength and ductility of the alloys listed in table #1. In conventional cast austenitic grades as well as duplexes, strength levels increase with increasing ferrite content as shown in figure #1. From a rule-of-mixtures perspective, this fact would suggest that ferrite is the stronger phase. This is the case for low nitrogen alloys. However, the compositional changes required to increase ferrite content also serve to strengthen austenite. In 1st generation duplexes, characterized by low nitrogen, ferrite is the stronger phase. In the 2nd generation materials, the austenite phase has the higher yield strength.

The corrosion resistance of the duplex stainless steels is the other primary material property for which they are selected. High resistance to general chloride media corrosive attack, chloride stress corrosion cracking, intergranular corrosion and pitting corrosion are features of the duplex family. Elevated levels of chromium and molybdenum promote this enhanced resistance to corrosive attack. Table #3 shows the critical crevice temperature, a measure of corrosion susceptibility, for several materials.

The pitting corrosion resistance of stainless steels can be summarized by the pitting resistance equivalent (PRE). The PRE is calculated from the composition and is based on empirical correlations with corrosion performance. The most widely held formula for the factor is:

$$PRE = \%Cr + 3.3\ \%Mo + 16\ \%N$$

The coefficients used in the index are subject to debate with the effectiveness of nitrogen ranging from 10 to 30. The PRE defines a continuum of corrosion resistance levels beginning with the austenitic stainless grades such as 316, the duplex alloys like 2205, the "super-duplexes" such as 2507 and finally the "super-austenitics", 254-SMO® for example.

The toughness of the duplex alloys is excellent, provided proper solution heat treatments are employed and that elevated service temperatures are avoided. The upper use temperature for most duplexes is about 600°F. Above this temperature, several forms of embrittlement become troublesome. In the 1300-1750°F range, sigma phase forms. Between 600-1000°F, a number of undesirable phases can precipitate. Most of these phases are brittle and contain chromium, which depletes the alloy upon precipitation and reduces corrosion resistance. Duplex grades are not suitable for cryogenic applications as ferrite is subject to cleavage fracture. However, the large volume fraction of austenite in the alloys serves to toughen these materials at low temperatures relative to completely ferritic alternatives.

METALLURGY

The amount of ferrite present in the alloys can be predicted from composition through the familiar Schoefer Diagram shown in figure #2. This diagram can be found in ASTM A 800. The coefficients used to calculate nickel and chromium equivalents are based upon the relative potency to stabilize each phase.

Microstructures composed of approximately equal amounts of ferrite and austenite are optimum and possess high values of interphase boundary area per unit volume. This interphase boundary is a preferred location for the nucleation of carbides and intermetallic precipitates. Precipitation of otherwise harmful phases on the austenite-ferrite boundaries results in a very narrow chromium depleted zone and allows "healing" to occur. Healing is a process in which locally depleted chromium is resupplied by diffusion from the austenite phase.

Figure #3 shows a microstructure typical of this class of alloys (2205 in this case). The sequence of phase evolution during solidification of the duplex alloys depends on composition. Solidification can begin with primary ferrite or primary austenite. In either case, much of the microstructure results from transformation during cooling rather than from equilibrium solidification.

CASTABILITY

For the most part, users of 2nd generation duplexes report castability similar to the 300 series stainless steels. The benefits of some ferrite in the structure of austenitic stainless steels is well known. Hot tearing resistance is improved as well as a general increase in strength and corrosion performance. This is the case with the duplex alloys. While the alloys do contain intentionally high nitrogen contents, the high chromium levels lower the activity of nitrogen, effectively raising the solubility. Deoxidation or degassing practices which would ordinarily be used to control nitrogen are not appropriate. Additions of titanium, zirconium or aluminum should be avoided. Most users simply melt and pour.

When diagnosing casting problems, casters should avoid being quick to blame the high nitrogen contents of these alloys for defects which appear similar to soluble gas defects in austenitic or ferritic grades. Slow solidification rates, in heavy sections for example, can "push out" enough nitrogen to exceed the solubility limits in some cases, forming gas holes or spongy areas near section centerlines. This appears to be rare. Most examples of gas problems can be eliminated with adequate mold venting and pouring to produce laminar flow into the mold.

Care must be used in the sequencing of the duplex alloys to avoid contamination. The ferrite content depends on composition which can be changed by pickup from furnace and ladle skulls. The alloys are capable of tolerating most other stainless grades as well as a limited amount of nickel base alloys (Ni B, Ni C, Ni X). However, avoid following tool steels or high carbon steels and irons. All the duplexes are low carbon grades and the ferrite fraction is a strong function of carbon content.

Argon covering is not required. Pouring temperatures are typically in the 2750°-2900°F range. The carbon content of these alloys is generally less than 0.02% so the fluidity is similar or slightly better than 316L. The use of foundry revert as a portion of the charge is acceptable. Again, attention must be paid to composition.

HEAT TREATMENT

Heat treatment of the duplex grades is critical for developing optimum corrosion and mechanical properties. Deleterious intermetallic phases are dissolved upon high temperature solution heat treatment. These phases do not precipitate on cooling provided adequate quench rates are used. Water quenching is usually employed. Shown in table #4 are the minimum solution heat treat temperatures, as called out by ASTM A-890, for duplex stainless castings. Additional time these alloys is an absolute necessity and industry standard minimum temperatures must be recognized as minimums. The duplex stainless steels are readily investment cast. With reasonable care and attention, good quality castings, with a minimum of scrap and rework, can be obtained.

Table #1
Compositions

grade	C*	Cr	Ni	Mo	Cu	[N]	Fe	PRE	type**
316L	.03	19	9	3	-	-	bal	29	AUS
CN-7M	.07	20	29	2.5	3.5	-	bal	29	AUS
329	.08	26	4.5	1.5	-	-	bal	31	DSS-1
CD4-MCu	.04	25	5	2	3	-	bal	32	DSS-1
CE8-MN	.08	24	9	4	-	.2	bal	40	DSS-2
Ferralium 255®	.03	25	6	3	2	.2	bal	38	DSS-2
2205	.03	22	5	3	-	.15	bal	35	DSS-2
2507	.03	25	7	4.5	-	.20	bal	43	DSS-2
Avesta 254 SMO®	.03	20	18	6	0.7	.2	bal	43	AUS

*maximum
**AUS=austenitic; DSS=duplex, 1st or 2nd generation

Table #2
Mechanical Properties

grade	UTS	YS	% el
316L	70	25	40
CN-7M	80	35	30
329	90	70	15
CD4-MCu	100	70	16
CE8-MN	95	65	25
Ferralium 255®	110	80	15
2205	90	65	25
2507	110	80	20
Avesta 254 SMO®	90	40	40

and temperature, over the minimums specified, may be required to develop full strength and ductility in these alloys.

Heat treatment is usually carried out in air. Vacuum or protective atmospheres can be used during the high temperature solution heat treatment to reduce or eliminate the scale produced in air. This becomes more important when longer times and higher temperatures are involved.

MACHINING

Duplex stainless steels are strong materials. This dictates the use of rigid, high horsepower machines combined with sharp carbide cutting tools and low machining speeds and feeds. A 40-50% speed reduction over austenitics for rough machining is required. Finishing speeds reduced 75-80% over those used to machine austenitic grades give good surface finishes.

WELDING

Duplex stainless steels offer substantial improvement in weldability over the austenitic grades. Post-weld solution heat treatment is a requirement of most austenitic grades to restore corrosion resistance. However, second generation duplex alloys have the ability to be used in the as-welded condition. The intentional nitrogen addition stabilizes austenite in the heat affected zone. Filler compositions generally match the base alloy or are enriched in nickel and nitrogen to increase the austenite content of the weldment. High heat inputs and or preheating are used to slow down the cooling rate in order to develop the proper 50/50% mixture of ferrite and austenite. All areas to be welded should be carefully cleaned to avoid contamination, especially from carbon from grease or cutting oils. Solution heat treatment is recommended following welding of the first generation duplexes.

CLEANING

Castings must be cleaned before being placed in service. All investment shell, scale from heat treatment or heat tint from welding should be removed. Glass bead or nonmetallic abrasive blasting is preferred over iron shot blasting which can leave a less passive iron deposit. Acid pickling is recommended for maximum corrosion resistance.

INGOT PRODUCTION

While the duplex grades can be produced in the induction furnace, the low carbon contents and intentional nitrogen alloying would make this an expensive proposition. A more practical and economical alternative is to manufacture these alloys using the AOD (argon-oxygen-decarburization) refining process. The AOD process facilitates carbon removal to less than 0.01%, allows the addition of nitrogen gas directly into the melt and reduces sulfur to less than 50 ppm. (thus lowering MnS inclusion levels).

CONCLUSIONS

In conclusion, duplex stainless steels offer exceptional strength and corrosion properties compared to the austenitic and ferritic grades of similar cost. Compositional control is important, in the master alloy manufacture as well as in the investment casting process. Heat treatment of