Self-Shielded Flux Cored Arc Welding for Steel Constructions – Productivity and Performance

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摘要：选择正确的焊接方法和焊材是在任何一个工程上保证最大成功的基本要素。如果不懂得关键特性和各种不同选择所带来的益处，就不能做出最终的决定。本论文阐述了自保护药芯电弧焊过程的关键特性在生产率和性能方面表现出来的优点。 回顾过去 46 年的设计方法历史就能说明加工过程和焊材两者的革新在本文所提及的过程中的应用，这种应用为加工过程带来了最大的收益。

FCAW-S 独特的连接工艺使其能不断地应用在各种工业部门的钢材装配焊接上。例如包括建筑结构和基础构造工程，海上结构和管道。这些行业利用该工艺达到所需的焊接质量和焊接稳固性，而在焊接过程中不需要再使用外部气体的保护。由此提供了高效率连续送丝焊接的优点。

简单说来，FCAW-S 结合了焊条电弧焊（SMAW）的柔性和气体保护药芯电弧焊（FCAW-G）或者熔化极气体保护焊高生产率的特点。因而，在气体保护焊不易实现和高成本的情况下，FCAW-S 还是合乎使用。近年来为满足更好的结构设计并提供更高的焊接性能，制造商和焊接制造业需要发展创新的方法来维持生产力的优势，而 FCAW-S 正提供了在那些情况下的应用。

关键词：自保护药芯焊接　钢结构　生产率　性能

Abstract: Selecting the right welding processes and consumables for an application is essential to maximizing the success of any project. Informed decisions cannot be made without an understanding of the key features and benefits for the various options. This paper reviews the key features of the self-shielded flux cored arc welding (FCAW-S) process in terms of productivity and performance advantages. A review of design approaches over the 46 year history of the process explains the evolution of both the process and consumables in the context of the applications where the process offers the greatest benefits.

The combination of key technologies that make FCAW-S possible is unique and is the reason for continuing demand for the process in several industry sectors for welded steel fabrication, Figure 1, including building construction and infrastructure projects, offshore structures, and pipelines, to name a few. These industries take advantage of the ability to achieve weld quality and soundness without the use of an externally supplied shielding gas with a welding process that offers the productivity advantages of continuous wire.

Simply stated, FCAW-S combines the flexibility of shielded metal arc welding (SMAW) with the productivity of gas-shielded flux cored arc welding (FCAW-G) or gas metal arc welding (GMAW or GMAW-C). Consequently, FCAW-S has found and maintained a “niche” in industries where use of a shielding gas is impractical and/or cost prohibitive. Demands for higher levels of weld performance to accommodate advances in structural design in recent years have challenged both fabricators and welding manufacturers to develop innovative solutions to maintain the productivity benefits that FCAW-S offers in those “niche” applications.

This paper reviews the key technologies and demonstrates what makes FCAW-S an important consideration for achieving productivity and performance in welded steel construction.

Key words: Self shielded，Flux cored wire，Steel construction，Productivity，Performance

Figure 1 FCAW-S in Building Construction

Commonly known as Innershield® , FCAW-S is still the process of choice for field fabrication of steel structures of various types.

BACKGROUND

Welding has its origins in the carbon arc process [Ref. 1]. The welding consumable was born when the carbon was replaced with a bare electrode made from cold rolled steel. Welds were characterized by uneven fusion, porosity and large globular transfer. So, it is no wonder that the electrode designs were focused on taming the process and improving weld quality. The objectives were always the same – improved productivity and performance at a cost that was more favorable than the current standard at any point in history. SMAW quickly dominated industrial fabrication and spawned a century of research and development dedicated to improving productivity and performance.

It is important to recognize that productivity and performance are relative terms. In some instances, productivity gains can be achieved simply by increasing deposition rates. In others, it may involve improvements in operating characteristics to minimize the level of operator training and skill needed to produce welds to the required workmanship standards. Then there is the traditional trade-off relationship between productivity and weld performance. Often the actions taken to improve productivity adversely affect material properties (e.g. weld strength and heat affected zone hardness vs. weld cooling rate and heat input).

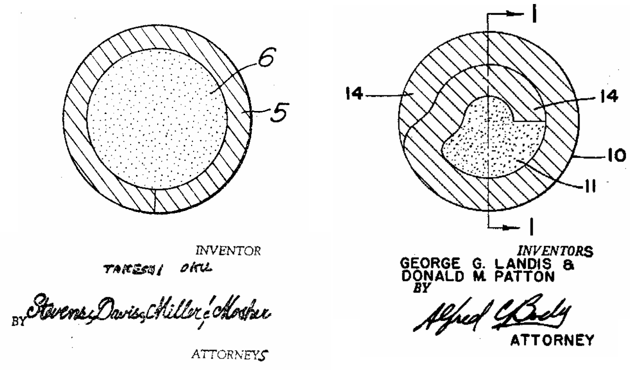
All of the continuous wire electrode arc welding processes were developed in direct response to the productivity limitations of SMAW. FCAW-S was one of several innovations that achieved commercial significance, each addressing industry demand for higher levels of productivity and performance in a different way.

What is FCAW-S?

FCAW-S was first developed in 1959 [Ref. 2] and introduced commercially as Innershield®. It is a continuous wire electrode that is tubular in cross-section. The outer sheath is made from ordinary strength steel. Alloy powders and flux for arc stabilization/slagging are delivered to the arc as fill inside an outer sheath, Figure 2.

It should be noted that the use of tubular wire electrodes started much earlier than 1959. This type of composite electrode had been used previously for the manufacture of highly alloyed electrodes of unique composition. [Ref. 3] Typically, a mild steel sheath was filled with alloy powders to produce chemical compositions that would have been extremely difficult, if not impossible, to fabricate as solid alloy wires. So, the concept of a flux core is not new, only the application to high productivity process for steel fabrication.

Since the SMAW electrodes for steel fabrication are characterized by an ordinary strength steel core covered by a cured coating containing powdered metals, oxides, fluorides and gas formers, often it is thought that FCAW-S wires are simply SMAW electrodes turned inside out. This is really a misconception because the small amount of gas produced by FCAW-S electrodes is not sufficient to act as a gas shield.



b) lapped seam

Figure 2 Typical Cored Wire Electrodes

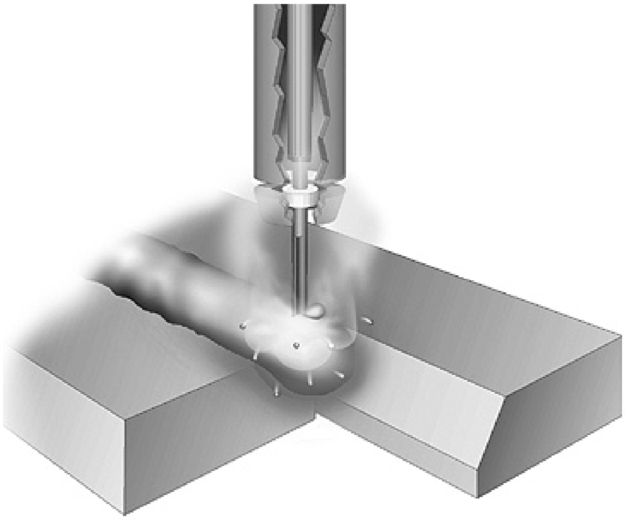


Figure 3 FCAW-S Innershield® Process

What Makes FCAW-S Different?

While it may be convenient to conceptualize FCAW-S in this way, it is not accurate and does not describe the key technology involved. There is no auxiliary shielding gas and very little opportunity to add gas formers to the electrode fill. Too high a concentration of gas formers in the fill will cause the press fit seams, which are typical of most FCAW products, to split open due to resistance heating of the electrode extension. What little gas is produced above the molten puddle tends to cushion the large droplet that forms, typically off the side of the electrode, Figure 3. Strong deoxidizers and denitriders are characteristic of all such consumables to deal with the inevitable atmospheric contamination of the weld pool, essentially killing the weld pool during the welding process.

Much of the early development in FCAW-S electrodes dealt with issues of arc stabilization and ductility reminiscent of the early development of bare and covered electrodes. Borrowing on the FCAW-S approach to kill the weld pool in place with strong deoxidizers/denitriders, a few bare solid electrodes were developed for open arc welding in the 1960's [Ref. 4, 5], but there is little evidence that they achieved major commercial significance.

Most welding processes require protection from wind during operations to ensure that the gas shielding that protects the arc from atmospheric contamination is not compromised. The single exception is FCAW-S because the process does not rely on shielding to achieve sound welds. This makes the process ideally suited to field fabrication of steel structures where shielding the welding operations is either cost prohibitive or not practical. For example, the process has been extensively for the fabrication of steel framed buildings, field welding of pipelines for gas and oil transmission, field construction and repair of both light and heavy gage steel structures.

FCAW-S slag systems are designed specifically to scavenge much of the oxygen and nitrogen contamination and to enable a large amount of off-gassing from the molten weld puddle. These features of FCAW-S also make many of the slag systems uniquely suited to welding over steel coatings, mill scale, and "dirty" base materials. For example, some E71T-14 [Ref. 6] are used specifically for high speed welding on galvanized, specialty zinc-coated, and aluminized steels 0.8 to 4.8 mm thick. The soft , low penetrating arc and fluid slag of some E70T-4 [Ref. 6] offer higher resistance to hot cracking when welding on high sulfur steels and resistance to porosity on rusty, oily or "dirty" steel plates.

KEY TECHNOLOGIES

The key technologies that distinguish FCAW-S from other arc welding processes are based on the slag/metal reactions that kill the molten metal during welding and the physical characteristics of the slag systems that ensure effective off-gassing of the molten puddle. The strong deoxidizers/denitriders and slag system design required to achieve the benefits of FCAW-S also represent certain performance challenges in other respects. As material systems, FCAW-S weld metals are relatively rigid without much flexibility for minor design modifications. The interaction between slag and weld metal composition is critical to both the weld metal properties and the operational characteristics that welders value. This makes is extremely difficult to improve operation without compromising weld properties and vice versa. As industry demands for higher levels of performance continue, the technological challenges for FCAW-S increase as well. The evolution of FCAW-S welding development illustrates how many of these challenges are met, Figure 4.

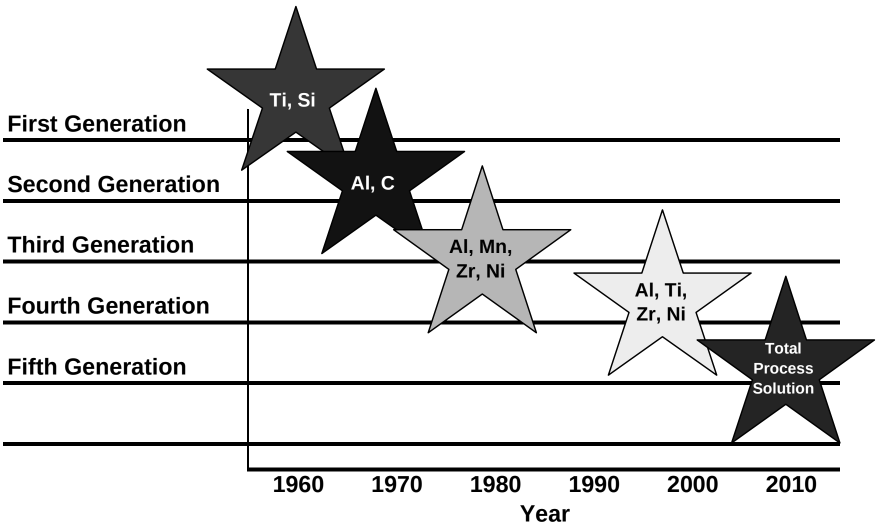


Figure 4 Evolution of FCAW-S Development

First Generation

The first commercially accepted FCAW-S electrodes were introduced to the automotive industry in the late 1950's. Designed primarily for productivity improvements on thin gage material, they relied on titanium for nitride formation and silicon for deoxidation. These relatively large diameter electrodes, 3.0 to 4.0 mm, were designed for high speed single pass welding in the flat and horizontal positions on base materials no more than 5 mm thick. The thickness limitation was a direct result of the hardening effect of Ti. The slag system physical characteristics ensured acceptable bead shape at speed.

Fillet weld metal composition is summarized in Table 1. However, it should be noted that productivity was the primary performance characteristic of interest to industry at the time. These results are from single-pass welds as described in the American Welding Society (AWS) conformance testing for these consumables. Weld metal chemical composition is not required for classification because of the strong dependence on base steel composition and dilution.

Table 1 Weld Composition, First Generation

AWS Class	Trade Name	C	Mn	Si	Al	Ti
E70T-3	NR-1	0.2	1.2	0.5	0.03	0.2
E70T-3	NR-5	0.2	0.9	0.4	0.08	0.5

Second Generation

Recognizing the limitations of the E70T-3 types, work was directed subsequently to the development of consumables for the multiple pass welding of steel without thickness limitations. Electrodes were introduced in the mid 1960's that satisfied the need for both minimum strength and ductility. The key to this development was the use of Al for both deoxidation and nitride formation. There was an optimum balance of C and Al necessary in order to achieve acceptable weld metal ductility. The fundamental reasons for this were not fully understood at the time, but became apparent in subsequent stages of development as researchers found ways to offset the influence of Al on phase stability in steel weld metals.

It should be noted that strength and ductility were the only performance attributes of interest other than productivity. Performance in AWS classification test welds is summarized in Table 2. All of the electrodes listed are still in use today. The E70T-4 and E70T-7 were introduced specifically for high productivity welding of steel frame buildings. Relatively high Al levels give these electrodes a large operating range. Using long electrical stick out and the largest of the available diameters (2.8 mm for E70T-7 and 3.0 mm for E70T-4) very high welding speeds could be achieved with acceptable weld quality at deposition rates on the order of 15 to 18 kg/hr, an order of magnitude higher than SMAW could offer.

Table 2: Weld Performance, Second Generation

AWS Class[Ref.6]	Trade Name	All weld metal tensile(a4)			C	Mn	Si	Al	S	P
		YS MPa	UTS MPa	% EL						
AWS Req.	—	400min	480min	22%min	—	1.75max	0.90max	1.8max	0.03max	0.03max
E70T-4	NS-3M	430	615	27	0..20	0.44	0.27	1.22	<.003	0.007
E70T-7	NR-311	450	620	23	0.25	0.48	0.10	1.36	<.003	0.007
E71T-7	NR-202	450	605	22	0.20	0.81	0.20	1.02	<.003	0.010
E71T-11	NR-211MP	505	665	24	0.27	0.71	0.17	1.50	<.003	0.007

*20% for E71T-11

The ETIT-11 listed is still one of the most versatile all-position FCAW-S for light steel fabrication where strength and ductility are the only weld metal requirements. It was designed specifically for operator appeal with relatively low spatter levels and weld bead appearance even when joint fit-up is not optimum.

Third Generation

By the mid-1970's, industries had become concerned with weld metal impact toughness as a measure of fracture resistance. Consequently, the third generation in FCAW-S electrodes targeted welding applications requiring Charpy V-notch (CVN) impact properties. Initially, modest CVN values at -18 ^oC (0 ^oF) and -29 ^oC (-20 ^oF) were required for most heavy structural steel fabrication. As growth in the energy sector placed higher demands on the offshore and line pipe industries, additional CVN requirements were imposed to ensure the structural integrity of welds, sometimes at temperatures as low as -40 ^oC (-40 ^oF).

Consequently, many of the third generation electrodes were alloyed with nickel and other alloy elements [Ref. 7]. The most important role of these alloy elements was to manage the influence of Al on phase stability in the FCAW-S weld metals. Figure 4 illustrates how Al creates a closed austenite loop in the phase diagram. In order to promote the low temperature microstructural transformations that contribute to higher levels of toughness, cooling through the austenite phase field is essential. Unfortunately, at the Al levels needed for favorable operating characteristics (~1 % by weight) this is difficult to achieve. Several of the alloy elements used in these electrodes have the effect of expanding the austenite phase field to higher Al contents. Table 3 summarizes the performance characteristics possible with several of these FCAW-S. Results are from AWS classification test welds. The toughness properties reported are achieved by optimizing welding practice and pass sequence for each electrode. The electrodes were designed specifically to take advantage of the grain refinement achieved by keeping individual weld passes small. The offshore industry maximized performance by taking advantage of this feature [Ref. 8].

Table3 Weld Performance, Third Generation

AWS Class	Application	Trade Name	All weld metal tensile(A4)			CVN@ -29C(J)	CVN@ -40C(J)
			YS（MPa）	UTS（MPa）	% EL		
E71T-8	Mild steel structures	NR-203MP	415	510	29	173	149
E71T-8	Mild steel structures	NR-232	490	595	27	60	—
E71T8-Ni1	Low alloy Structural	NR-203 Nickel 1%	465	570	30	95	—
E61T8-K6	Low alloy Offshore	NR-203 Nickel C	400	490	31	163	—
E71T8-Ni2	Low alloy Offshore	NR-450-H	425	520	27	106	—
E91T8-G	Low alloy Offshore	NR-460-H	581	670	26	84	102
E71T8-K6	Up to X65 Pipeline	NR-207	445	550	30	204	—
E71T8-K6	X70 Pipeline	NR-207+	470	565	24	147	—
E91T8-G	X80 Pipeline	NR-208-H	565	650	27	71	—

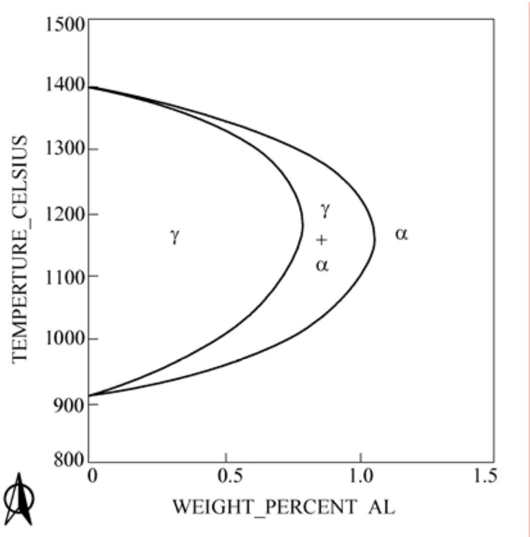


Figure 5 Phase Stability in FCAW-S

Practical limitations on the use of shielding gases for field welding of line pipe made FCAW-S the only viable alternative to SMAW. Table 4 illustrates one example of the cost benefit FCAW-S over SMAW as a direct result of higher operating factor and deposition efficiency. Savings on the order of 40% are fairly typical with FCAW-S. Repair rates are not included in the estimate as they are normally below 1%.

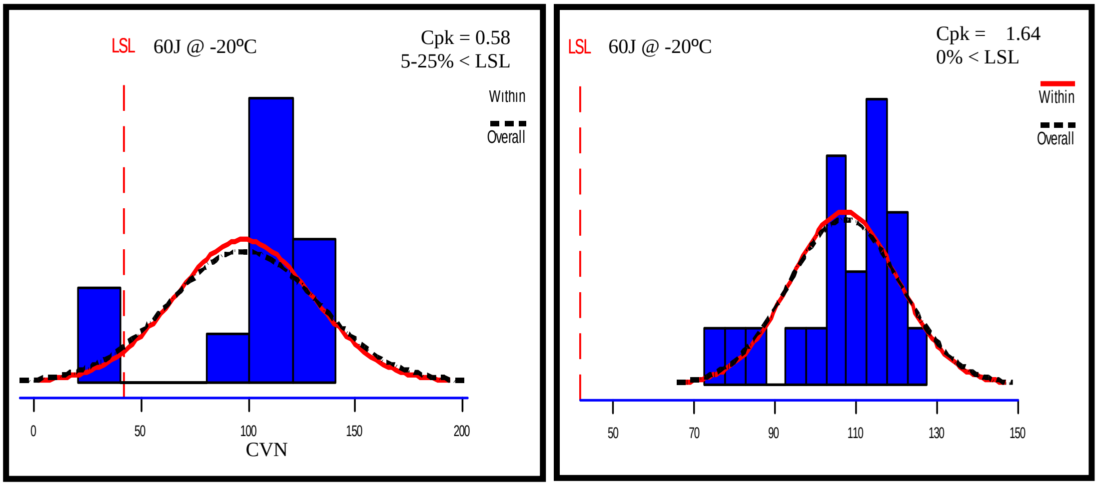
Table4 Cost Comparison (Australian $)

Item	SMAW	FCAW-S
Filler metal base cost	$6.65/kg (4.8mm)	$12.34 (2.0mm)
Deposition Efficiency	50%	83%
Operating Factor	25%	40%
Consumable/joint (filler metal base cost/efficiency)*5.76	$76.60	$85.69
Labor and Overhead (estimate)	$47.50	$47.50
Typical Procedure:	SMAW	FCAW-S
Amperage	170	250
Travel speed	30.5 cm/min	43.2 cm/min
Operating factor	25%	40%
No.of passes	7	6
Arc Time/joint	294 minutes	111 minutes
Labor Cost/joint:	186	70.22
Electrode cost/joint	76.6	85.69
Total	$262.60	$155.91

Fourth Generation

New performance demands were driven by a number of factors in the various industry sectors. Major seismic events around the world caused structural designers in the building construction industry to reconsider historical assumptions. This drove toughness requirements in a new direction – CVN in the transition region, -18℃ (0ºF), and at the upper shelf, 21℃ (70ºF) – as it became important to consider fracture behavior over a range of service temperatures. At the same time, more innovative designs were pushing strength and section thicknesses higher, both factors which led to a concern for the consistency of CVN measurements as well as the nominal energy levels at temperature.

Offshore and pipeline industries followed similar trends for higher strength and toughness in addition to concerns about greater control over diffusible hydrogen levels. Design innovations (i.e. strain based vs. stress based) in the pipeline industry also raised the bar with regard to tensile strain limits and consistency of CVN behavior. The concern over CVN consistency is illustrated in a typical process capability analysis for a third generation FCAW-S weld metal, Figure 5a. While the units are not particularly important, the bimodal nature of the CVN performance is fairly typical of these weld metals. Average performance satisfies expectations, but the isolated low can occur at a frequency of between 5 and 20%. For many applications, this poses no concern. For others, where risk tolerance is low, higher reliability in CVN performance is desirable.



a) Third Generation b) Fourth & Fifth Generation

Figure 6 CVN Process Capability Analysis, Third Generation

Consequently, the fourth generation electrodes are designed for greater consistency in mechanical properties as well as higher strength and toughness. The isolated low values are caused by microstructure discontinuities that nucleate cleavage too early – non-metallic inclusions over ~2 microns and brittle phases (i.e. MAC) along grain boundaries in relatively course bainitic microstructures. Controlling the size distribution of non-metallic inclusions, accomplished by rebalancing Al, Ti, and Zr, reduced the frequency of low values significantly (<5%). While this does not eliminate completely the bimodal character of the CVN distribution, the higher overall toughness results in greater reliability and confidence.

It is important to note that the efforts taken to improve the CVN performance, particularly at higher strength levels, require significant reductions in Al levels. This results in smaller operating windows, higher risk of porosity if operators stray too far from the optimum operating ranges, and very little flexibility for productivity improvements.

While other welding processes do not require such trade-offs to the same degree, the key advantage remains for FCAW-S in applications where shielding gases represent a significant burden on project operations.

Fifth Generation – Vision For The Future

The needs of the building construction industry for heavy fabrication have been satisfied by the key technologies developed in the third and fourth generation FCAW-S electrodes. Until significantly new innovations in structural design push the applications to the point where new failure modes occur, simple evolutionary improvements in operation are expected to satisfy the needs for the near future. The needs of the offshore industry are likely to be served simply by expanding the fourth generation technology to a broader range of FCAW-S electrodes. However, the pipeline industry is expected to continue pushing beyond the bounds of existing technology.

For structural designs that are intended to experience engineering strains in excess of yield – whether due to forces of nature or intentional loading – the shift to higher strength materials will require even higher levels of toughness. The slag system and alloy changes that characterized the evolutionary changes in welding consumables will not be enough for the performance levels anticipated in the next five years.

The inherent limitations of conventional FCAW-S technology have been optimized. Further substantial improvements are not achievable with chemical composition alone. It has been demonstrated that the key to weld metal properties and performance is control of the microstructure. To fully optimize the weld microstructure requires control of both the chemical composition and the weld thermal cycles. Up to this point, the only attention given to the process side of the equation involved heat input limitations and selective bead placement to maximize grain refinement. The next step will be to tailor weld metal microstructures by optimizing the entire welding process.

Continued viability of the FCAW-S process will be assured through the development and commercialization of total process welding solutions.

SUMMARY & CONCLUSIONS

The benefits of FCAW-S have been reviewed in the context of the key industry segments – building construction and infrastructure projects, offshore structures, and pipelines. The ability to weld without the need for a shielding gas is major advantage in these industries. The key technologies that make this possible and distinguish FCAW-S from other arc welding processes are based on the slag/metal reactions that kill the molten metal during welding and the physical characteristics of the slag systems that ensure effective off-gassing of the molten puddle. The interaction between slag and weld metal composition is critical to both the weld metal properties and the operational characteristics that welders value. This makes it extremely difficult to improve operation without compromising weld properties and vice versa.

This review demonstrated that technology development made it possible to advance the state of the art in FCAW-S from the basic considerations of productivity and operator appeal to a complex set of interactions among mechanical properties requirements, operation, and productivity.

The key technologies involved optimizing different groups of alloy elements to achieve specific performance targets. This kind of evolutionary change was successful in satisfying the demands of industry up to now. A shift in technology development to total process solutions is expected to keep FCAW-S viable for those applications where shielding gas is a costly burden.

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