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IMPACT OF FLUX ON THE FABRICATION AND SERVICE WELDABILITY OF SUBMERGED ARC WELD DEPOSITS

UTICAJ TOPITELJA/PRAHA NA ZAVARLJIVOST VAROVA POD PRASKOM

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Abstract

Submerged arc welding (SAW) involves two consumables: a wire or strip electrode and a granular flux. The properties of the flux play a critical role in achieving the desired service properties of welded joints and deposits, as well as ensuring process flexibility for specific industrial applications. In the present study, the flux composition and the resulting slag properties are analyzed and compared across different application fields. The influence of flux grain size on weld metal properties and fabrication weldability is also examined. A range of structural welding fluxes, from manganese-silicate to fluoride-based basic types with varying basicity indices, together with alloyed surfacing fluxes, are evaluated and assessed. The contributions of manganese and silicon from the flux to the weld metal are evaluated and slag solidification behavior is analyzed. The relationship between slag characteristics and mechanical performance is investigated, with particular emphasis on impact toughness. For alloyed fluxes, the effect of heat input on the final properties of the weld deposit is additionally evaluated. Finally, the current-carrying capacity of the is assessed.

Rezime

Zavarivanje pod praškom se sastoji iz dvije komponente: žica (puna ili punjena)/traka i topitelja/praška. Svojstva topitelja su veoma važna u cilju ostvarivanja željenih svojstava zavarai navara, kao i upotrebljivost topitelja za odredjenu primjenu. U ovom radu, svojstva topitelja i formirane šljake su analizirana za različite primjene. Takođe, veličina i raspored zrna topitelja su važni kako za postizanje željenih svojstava tako i za priraštaj legirajućih elementa iz sastava topitelja. Dijapazon topitelja od mangansko-silicijumskih do visoko bazičnih fluoridnih sa različitim indeksom bazičnosti, kao i visokolegirajućih navarnih topitelja, je upoređen i analiziran. Doprinosi mangana i silicijuma su analizirani kao i svojstva formirane šljake. Veza između mehaničkih svojstava, posebno udarne žilavosti, je takođe analizirana. Sa legirajućim topiteljima veza između priraštaja toplote i svojstava je uspostavljena. Topitelji su testirani na njihov kapacitet zavarivanja sa maksimalnom jačinom struje i napona zavarivanja.

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1. Introduction

The main advantages of the SAW process (Figure 1) include the following [1]:

- high deposition rates and high productivity
- high operating factor
- minimal surface finishing time
- high travel speeds
- deep penetration (for structural components)
- low hydrogen levels
- reduced requirements on operator skills
- low levels of fumes and arc flash

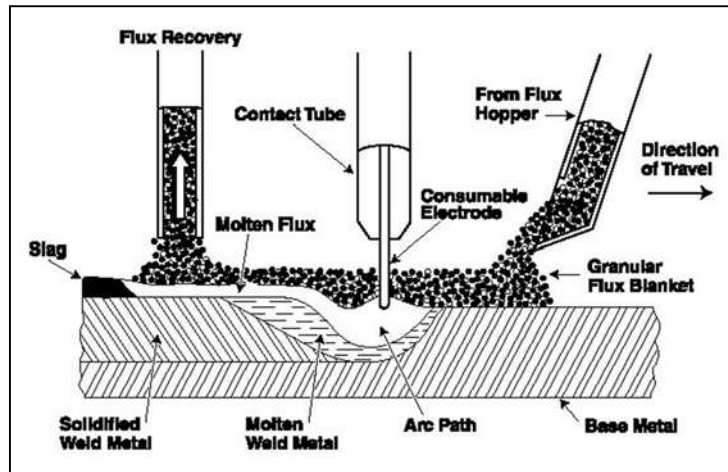


Figure 1. Submerged Arc Welding Process (SAW).

Slika 1. Postupak elektrolučnog zavarivanja pod praškom (EPP).

Conventional SAW employs three fundamental electrical operating modes, as illustrated in Figure 2 [2]. Direct current (DC) welding has commonly been the preferred option for SAW applications. DC electrode-positive (DCEP) polarity is the more frequently used operating mode and is characterized by deep weld penetration. DC electrode-negative (DCEN) is typically selected when minimal dilution is required. However, DCEN is more susceptible to magnetic arc interference

(arc blow) and porosity formation. Alternating current (AC) is most often employed when resistance to arc blow is crucial, particularly in multiple-arc configurations or in combination with a DC arc and additional AC arcs. The use of modern inverter technology, incorporating waveform control through adjustments in wave balance, amplitude, and frequency enables polarity switching without requiring hardware configuration modifications.

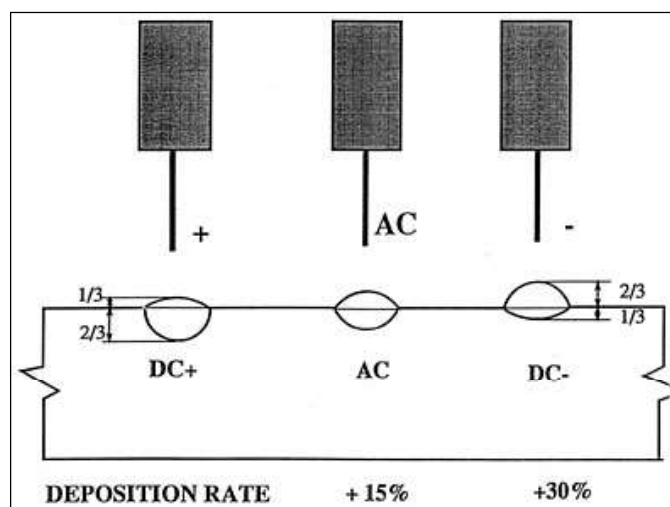


Figure 2. SAW operating modes.

Slika 2. Radni režimi EPP postupka.



Although significant attention is given to power sources and welding wires, a thorough understanding of flux selection and its influence on the SAW process is essential to achieve fabrication objectives and ensure adequate service weldability of the deposited weld metal. SAW fluxes consist of mineral constituents mixed with silica and are either agglomerated (600-850 °C) or fused (1,200-1,400

°C), then sieved to a particle size range of 10-80 mesh (Figure 3). While smaller particle sizes can sustain higher welding currents, an excessive proportion of fines in the flux may lead to gas entrapment between the slag and the weld pool. This can result in surface defects such as gas flats or pockmarking on the weld bead surface.

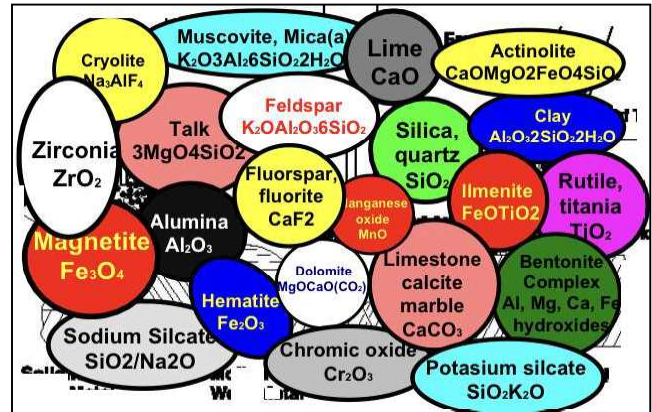
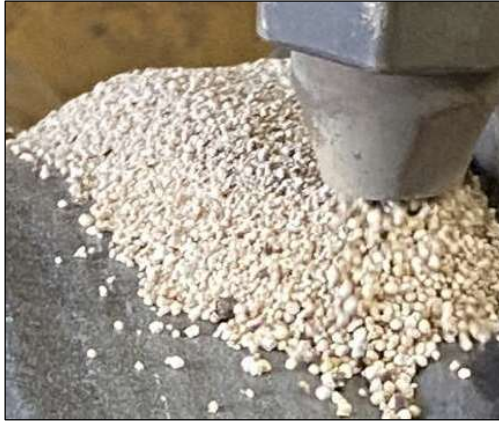


Figure 3. Typical composition of common minerals used for flux design [2].

Slika 3. Tipičan sastav uobičajenih minerala koji se koriste za pravljenje praška (fluksa) [2].

The primary functions of fluxes in the SAW process is to provide arc stability, ensure electrical conductivity in the molten state, shield the molten weld pool from atmospheric contamination, refine the liquid weld metal by removing impurities, control the weld metal cooling rate and weld bead profile, introduce alloying elements, and influence bead appearance.

SAW fluxes can be classified as follows [2]:

- active;
- neutral
- alloy fluxes;

The characteristics of active and neutral fluxes are evaluated using the following criteria:

- a) **wall neutrality number:** $N = 100 (|\Delta\%Si| + |\Delta\%Mn|)$. For a flux-electrode combination to be considered neutral, the value of N should be 35 or less. The lower the value of N, the more neutral the flux.
- b) **pick-up and burn-out behavior.** To determine pick-up and burn-out characteristics, a wire electrode conforming to ISO 14171-A – S2 or ISO 14171-B – SU22 shall be used in accordance with Section 5.5.6. The pick-up or burn-out of

silicon and manganese shall be reported in this sequence [7]:

- If %Si and %Mn in the deposited metal are greater than those in the S2 wire → active flux
- If %Si and %Mn in the deposited metal are equal to those in the S2 wire → neutral flux
- If %Si and %Mn in the deposited metal are lower than those in the S2 wire → non-active flux

Fluxes are also categorized according to the Basicity Index (BI), which is calculated as follows:

$$B.I = \frac{[CaO + MgO + BaO + CaF_2 + Na_2O + K_2O + 0,5 * (MnO + FeO)]}{[SiO_2 + 0,5 * (Al_2O_3 + TiO_2 + ZrO_2)]}$$

Acid fluxes: BI = 0.5-0.8 (< 2); oxygen content: >750 ppm. Acid fluxes contain silicates in the form of calcium and/or manganese silicates and manganese oxide. They exhibit low toughness but are tolerant of rusty or oily surfaces, with excellent slag detachability and bead appearance. Higher silica levels tend to produce slag that is more difficult to remove, whereas higher lime (CaO) contents result in slag that is easier to remove. Acid fluxes produce slag with a lower melting range than that of the weld metal.



Neutral fluxes: $BI=0.8-1.2 (< 2)$; oxygen content: 550-750 ppm. Neutral fluxes contain low levels of alumina, calcium silicate, and silica. Single-pass welds with insufficient deoxidation on heavily oxidized base metal may be susceptible to porosity, centerline cracking, or both. Neutral fluxes produce slag with a lower melting range than that of the weld metal.

Basic Fluxes: $BI=1.2-2.5 (> 2)$; oxygen content: 300-550 ppm. Basic fluxes contain combinations of calcium carbonate, and/or fluorides, alumina, magnesium oxide, and manganese oxide. The slag produced by basic fluxes solidifies at a temperature similar to or higher than that of the weld metal and is typically self-detaching. These slags provide improved, including performance at $-40\text{ }^{\circ}\text{C}$.

Highly basic fluxes: $BI=2.5-4.0$; oxygen content: <300 ppm. Highly basic fluxes exhibit low slag viscosity and limited current-carrying capacity. They provide excellent low temperature toughness, including performance at $-60\text{ }^{\circ}\text{C}$. Basic slag systems are highly effective in reducing weld metal oxygen content, thereby enhancing weld metal toughness; however, they tend to produce slags with lower solidification temperatures.

Fluxes can also be classified according to their solidification behavior as follows:

- **“fast-freeze”** fluxes are formulated to solidify rapidly, minimizing weld pool displacement before solidification. These fluxes enable rapid weld metal solidification, which is advantageous when welding joints with poor fit-up. Fluxes containing TiO_2 produce faster-freezing slag; for example, AR-type (aluminate-rutile) fluxes minimize spillage in circumferential welding applications. They allow maximization of arc speed and deposition rate and are a suitable choice for flash-through conditions.
- **“fast-fill”** fluxes are designed to melt quickly, thereby permitting higher welding. For example, MS1-type (manganese-silicate) fluxes are applied at low arc speeds and in situations where arc-blow-induced porosity is problematic.
- **“fill-freeze” or “fast-follow”** represent intermediate types in which the molten weld pool solidifies more slowly than with fast-freeze fluxes, resulting in a more fluid slag system. For example, ZS-type (zirconium-silicate) fluxes are suitable for high-speed welding without undercut formation or voids defects.

Tables 1 and 2 show typical compositions [3] and properties [4] of submerged arc fluxes, whereas Figure 4 shows how slag freezing characteristics affect the appearance of the weld bead profile.

Table 1. Fluxes compositions according to EN ISO 14174 [3].

Tabela 1. Sastavi praškova prema EN ISO 14174 [3].

Symbol/Type	Composition/% by mass		Symbol	% by mass
MS (Manganese-silicate)	$\text{MnO} + \text{SiO}_2 \geq 50$		RS (Rutile-silicate)	$\text{TiO}_2 + \text{SiO}_2 \geq 50$
	$\text{CaO} \leq 15$			$\text{TiO}_2 \geq 20$
CS (Calcium-silicate)	$\text{CaO} + \text{MgO} + \text{SiO}_2 \geq 55$		AR (Aluminate-rutile)	$\text{Al}_2\text{O}_3 + \text{TiO}_2 \geq 40$
	$\text{CaO} + \text{MgO} \geq 15$			$\text{Al}_2\text{O}_3 + \text{CaF}_2 + \text{SiO}_2 \geq 55$
CG (Calcium-magnesium)	$\text{CaO} + \text{MgO} = 5 \text{ to } 50$		BA (Basic-alumina)	$\text{CaO} \geq 8$
	$\text{CO}_2 \geq 2$			$\text{SiO}_2 \leq 20$
	$\text{Fe} \leq 10$			$\text{Al}_2\text{O}_3 + \text{SiO}_2 \geq 50$
CB (Calcium-magnesium basic)	$\text{CaO} + \text{MgO} = 30 \text{ to } 80$		AAS (Acid-aluminium-silicate)	$\text{CaF}_2 + \text{MgO} \geq 20$
	$\text{CO}_2 \geq 2$	$\text{Fe} \leq 10$		AB (Aluminate-



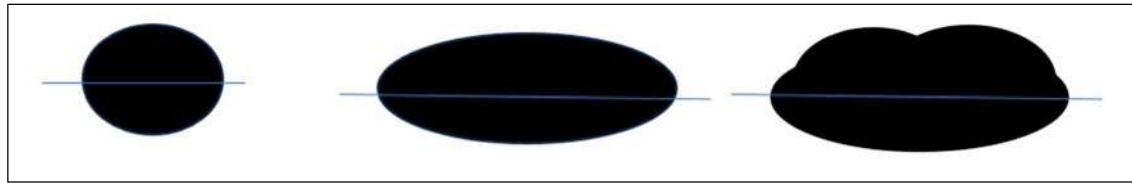
CG-I (Calcium-magnesium with iron)	CaO + MgO=5 to 45	basic)	Al ₂ O ₃ ≥20
	CO ₂ ≥2		CaF ₂ ≤22
	Fe=15 to 60	AS (Aluminate-silicate)	Al ₂ O ₃ +SiO ₂ +ZrO ₂ ≥40
CaO + MgO=10 to 70	CaF ₂ +MgO ≥30		
CB-I (Calcium-magnesium basic with iron)	CO ₂ ≥2	AF (Aluminate-fluoride-basic)	ZrO ₂ ≥5
	Fe=15 to 60		Al ₂ O ₃ + CaF ₂ ≥70
	GS (Magnesium-silicate)	MgO + SiO ₂ ≥42	FB (Fluoride-basic)
Al ₂ O ₃ ≤20			
CaO +CaF ₂ ≤14		SiO ₂ ≤20	
ZS (Zirconium-silicate)	ZrO ₂ +SiO ₂ +MnO ≥45	CaF ₂ ≥15	
	ZrO ₂ ≥15		

Table 2. Typical properties of submerged arc fluxes [4].

Tabela 2. Tipična svojstva praškova za zavarivanje pod praškom [4].

Properties	Flux Type				
	MS (Manganese-silicate) Acidic	CS (Calcium-silicate) Acidic	AR (Aluminate-rutile); Acidic	AB (Aluminate-basic); Basic	FB (Fluoride-basic) Basic
Amp Capacity	+++	+++	++	++	+
ACweldability	+(+)	++	+++	++	(+)
Porosity resistance	+++	++	++	++	++
Weldability	+	++	+++	++	+
Gaps bridging	+	++	+++	++	++
Arc Speed	++	++	+++	++	+
Detachability	+	+++	+++	++	++
Appereance	+++	+++	+++	++	+
H2 Cracking resistance	+	+	+	++	+++
Mechanicals	+	+	+	++	+++

+Normal; ++Good; +++Excelent



a)

b)

c)

Figure 4. Impact of slag freezing characteristics on weld bead profile: a) fast freezing slag, b) slow freezing slag, and c) slow freezing slag high round speed.

Slika 4. Uticaj karakteristika očvršćavanja šljake na profil zavarenog šava: a) šljaka sa brzim očvršćavanjem, b) šljaka sa sporim očvršćavanjem i c) šljaka sa sporim očvršćavanjem pri velikoj brzini zavarivanja.

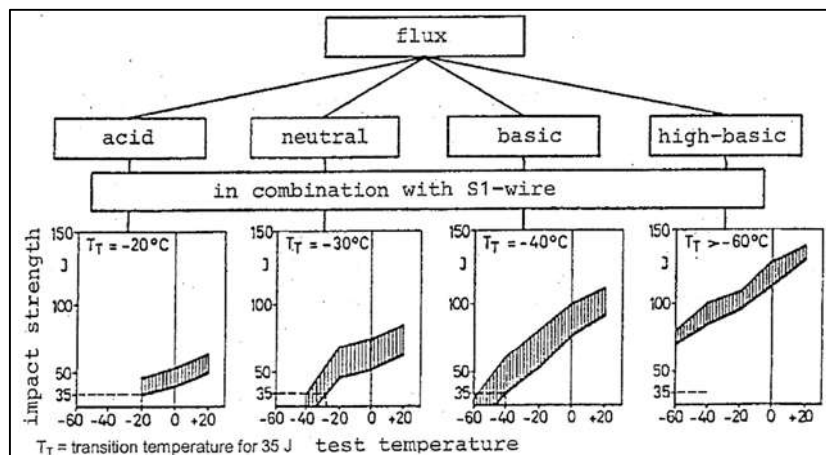


Figure 4. Impact of flux basicity on impact strength [4].

Slika 4. Uticaj baznosti praška na udarnu žilavost [4].

2. Experimental and analysis

The experiment involved an investigation of five different fluxes (Table 3), two types of MS (manganese-silicate) with different MnO contents and basicity indices (MS₁: MnO < 30% and BI =

0.77 and MS₂: MnO < 15% and BI = 0.88), AR (aluminate-rutile), which produces concave fillet welds prone to centerline cracking., ZS (zirconium-silicate), and AB (aluminate-basic), as listed in Tables 1 and 2.

Table 3. Investigated fluxes.

Tabela 3. Ispitivani praškovi.

Flux	Composition %										Slag
	SiO ₂	MnO	MgO	CaF ₂	Na ₂ O	Al ₂ O ₃	CaO	TiO ₂	ZrO ₂	FeO	
MS ₁	30-60	15-40	10-30	<20	<15	<10	<5	-	-	-	Slow freeze
MS ₂	25-50	15-25	18-25	<20	<20	<15	<7	<5	-	<5	Slow freeze
AR	<10	15-30	<8	5-12	<15	<60	<10	<20	-	-	Fast Freeze
ZS	21	<19	10-25	5-10	<10	2-20	<10	15-30	<20	<10	Fast follow
AB	19	10-16	10-30	<18	<10	20-40	<5	5-25	-	<3	Slow freeze



Manganese and silicon contributions to the weld deposit for the investigated fluxes are presented in Table 4.

Table 4. Manganese and silicon contributions of investigated fluxes.

Tabela 4. Doprinos mangana i silicijuma ispitivanih praškova.

Flux Contribution to Weld Metal Chemistry; With S1 wire	% Δ Mn	% Δ Si	Total %(Δ Mn + Δ Si)	B.I
MS ₁	0.8	0.49	1.29	0.77
MS ₂	1.08	0.59	1.67%	0.88
AR	0.77	0.43	1.20	0.78
ZS	0.69	0.57	1.26	0.73
AB	0.33	0.14	0.47	1.1

An extended investigation of manganese and silicon contributions is presented in Table 5 and Figure 5.

Table 5. Extensive overview of Mn and Si contributions of different fluxes.

Tabela 5. Opsežan pregled doprinosa Mn i Si kod različiti praškova.

Flux Contribution to Weld Metal Chemistry (S1 wire)	Total %(Δ Mn+ Δ Si)	B.I.	Flux Contribution to Weld Metal Chemistry (S1 wire)	Total %(Δ Mn+ Δ Si)	B.I.
AB/AR ₈₉	0.82	0.6	**AB _(TS01)	0.60	1.25
AS/AR ₉₇	1.04	0.69	AB ₅₉₁	0.71	1.29
MS ₁₋₀₆	1.29	0.77	AF _{02P}	-0.1	1.6
AR ₀₈	1.2	0.78	AB ₂₈	0.33	1.61
MS ₂₋₁₆	1.67	0.88	FB ₀₈	0	2
* MS _{3-16S}	2.98*	0.93	AB/CS ₀₂	0.05	2.17
AB ₆₈	0.47	1.1	FB/CS ₀₁₀₁	0.01	2.86
AB ₆₉	0.6	1.11	FB _{0N8}	0.29	2.86
AB ₅₉	1.02	1.25	FB ₅₈₅₈	0.12	2.86

*/** Not included in graph. * After high-speed welding of light poles with MS₃ and SU25 wire there was a reaction with a galvanizing solution. Problem was resolved by using S1 wire.

**% Δ Cr 2.4; MS₁₋₀₆; AR₀₈ FB_{0N8} self-peeling slag; AB₂₈ MS₂₋₁₆ Left gray adhering layer difficult to remove, bulk of slag detaching easily; FB₀₈ Slight levering slag detaching in one piece; AB₂₈ hard removing slag.

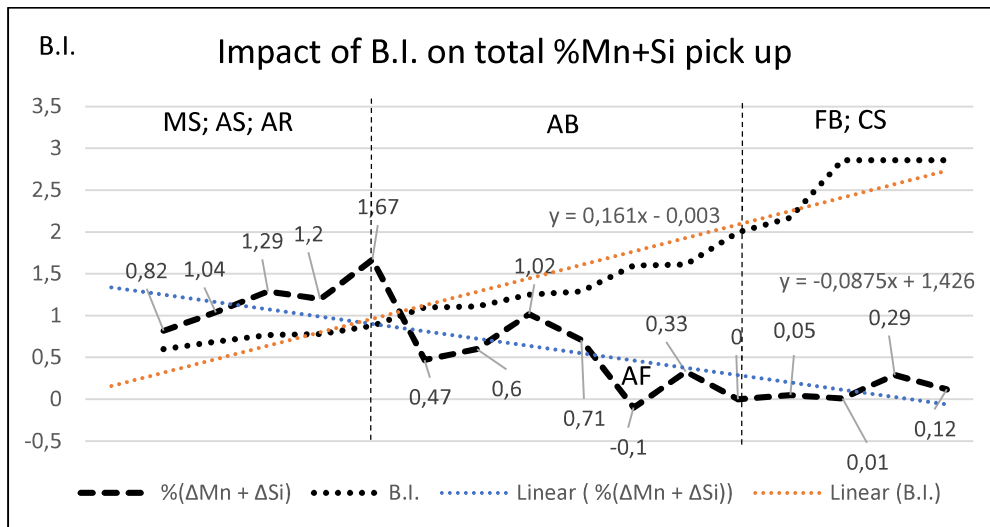
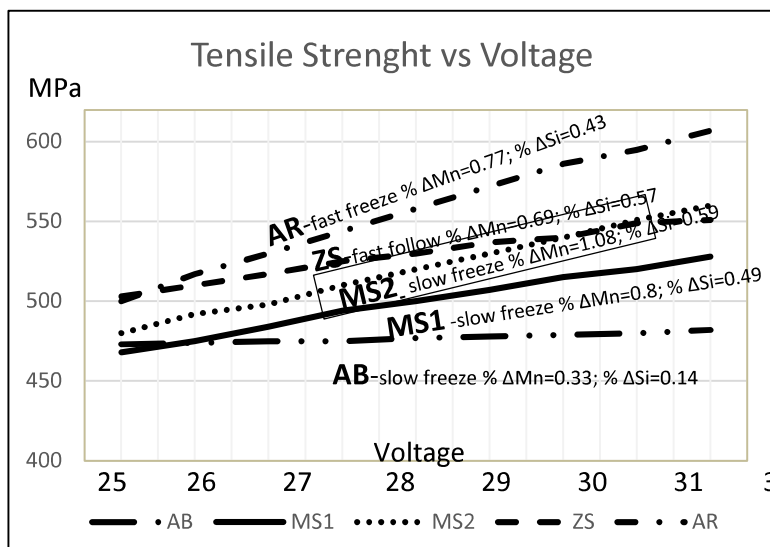


Figure 5. Mn and Si contributions across different investigated fluxes.

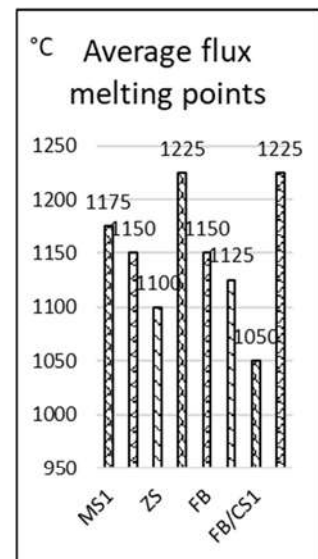
Slika 5. Doprinosi Mn i Si kod različitih ispitivanih praškova.

Further investigation included the effect of voltage on the tensile strength of selected fluxes

(Figure 6), as well as the effect of voltage on AB flux (Table 6 and Figure 7).



a)



b)

Figure 6. a) Impact of arc voltage on Tensile Strength of investigated fluxes AR; ZS; MS2; MS1; AB. Testing condition DC+ 550Amps Travel speed 410mm/min; Electrical Stick out 32mm; 4.0mm EN ISO 14171-A S1 wire and b) Average flux melting points.

Slika 6. a) Uticaj napona električnog luka na zateznu čvrstoću kod ispitivanih praškova AR, ZS, MS2, MS1 i AB; uslovi ispitivanja: DC+ 550 A, brzina zavarivanja 410 mm/min, električni izbačaj elektrode 32 mm, žica 4,0 mm EN ISO 14171-A S1 i b) prosečne tačke topljenja praškova.

Table 6. Impact of arc voltage on AB flux with 4.0 mm electrode ISO 14171-A: S2Si; Electrical Stick out 35mm.

Tabela 6. Uticaj napona luka na prašak AB pri upotrebi elektrode prečnika 4,0 mm (ISO 14171-A: S2Si); električni izbačaj elektrode 35 mm.

Flux AB		Travel Speed (mm/min)	Charpy - Energy					H.I. kJ/mm	
Amps	Volts		J @-20 C				Aver.		
600	28	410	104	107	126	140	133	122	2.46
600	33	410	58	56	82	80	67	68.6	2.90

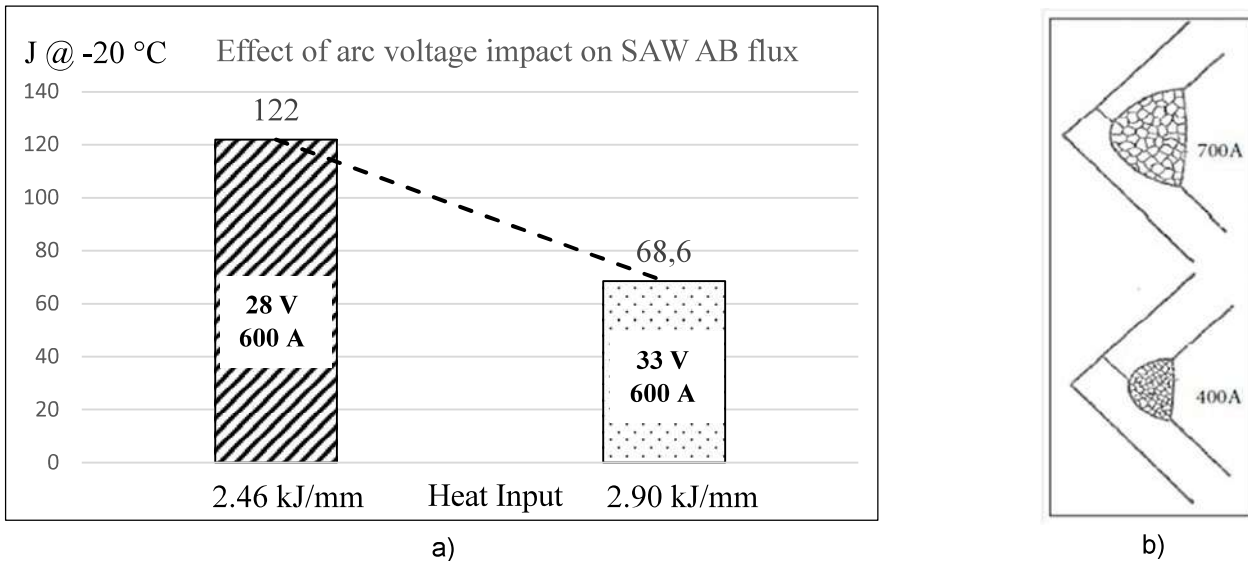


Figure 7. a) Impact of arc voltage on impact resistance of AB flux. AB flux, 4.0 mm electrode ISO 14171-A: S2Si; Electrical Stick out 35mm. and b) grain size of the weld made at 700A; 34V and 380 mm/min arc travel speed, heat input 3.74 kJ/mm and at 400 A;

Slika 7. a) Uticaj napona luka na udarnu žilavost praška AB. Prašak AB, elektroda prečnika 4,0 mm, ISO 14171-A: S2Si; električni izbačaj elektrode 35 mm; b) veličina zrna zavara dobijenog pri: 700 A, 34 V i brzini zavarivanja 380 mm/min (unos toplote 3,74 kJ/mm) i pri 400 A

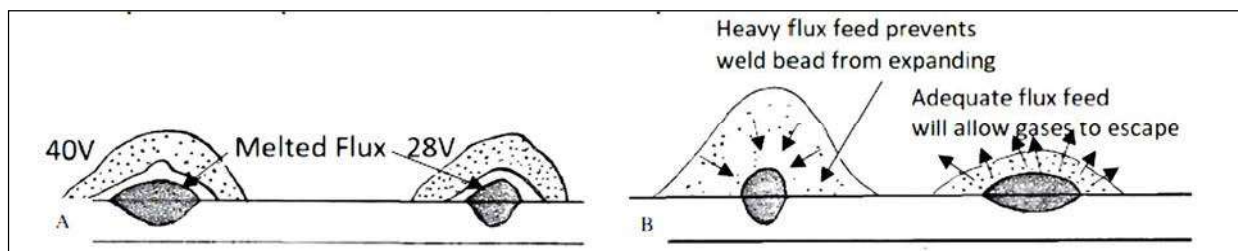


Figure 8. (A) Impact of arc voltage on bead/slag shape and flux consumption. High voltage melts more flux. (B) impact of flux feed on weld bead and gas discharge.

Slika 8. (A) Uticaj napona luka na oblik zavarenog šava/šljake i potrošnju praška. Veći napon dovodi do topljenja veće količine praška. (B) Uticaj dodavanja praška na oblik zavarenog šava i oslobađanje gasova.

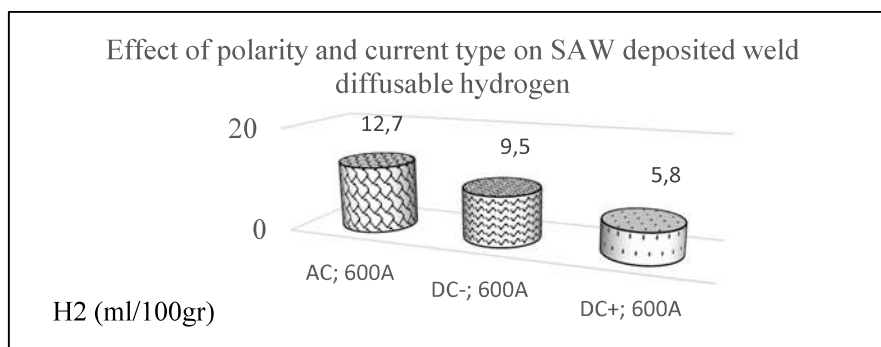


Figure 9. With the Submerged Arc Welding process an impact of current type is significant. Alternating Current (AC) produces twice the hydrogen (H₂/100gr) level of DC+. Low arc voltage on DC+ will help minimize hydrogen levels in submerged arc welds [5].

Slika 9. Kod postupka zavarivanja pod praškom značajan je uticaj vrste struje. Naizmjenična struja (AC) proizvodi približno dvostruko veći sadržaj vodonika (H₂/100 g) u poređenju sa DC+. Niži napon luka pri DC+ pomaže u smanjenju nivoa vodonika u zavarima izvedenim postupkom zavarivanja pod praškom [5].

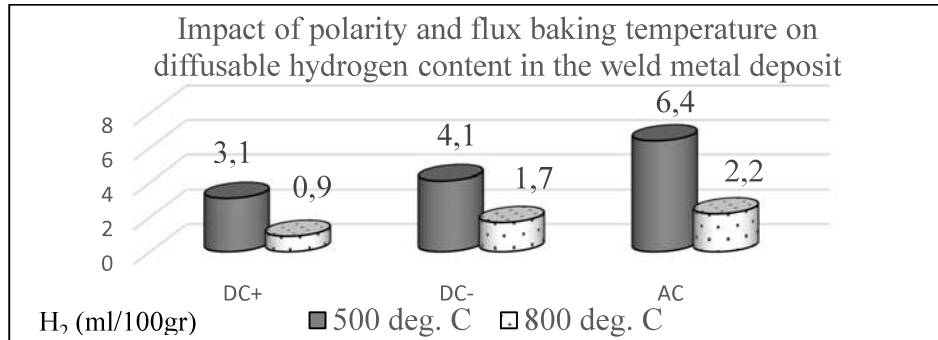


Figure 10. The effect of flux baking temperature and current in submerged arc welding process [5].

Slika 10. Uticaj temperature sinterovanja praška i struje u postupku zavarivanja pod praškom [5].

3. Conclusions

The complex nature of numerous available submerged arc welding fluxes requires a selective approach to meet fabrication and service weldability requirements of the welded joint. Flux design performance affects weld bead properties and is also dependent on welding parameters.

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3. Zaključak

Složena priroda brojnih dostupnih praškova za zavarivanje pod praškom zahtijeva selektivan pristup kako bi se ispunili zahtjevi za izradivost i upotrebljivost zavarenog spoja. Performanse dizajna praška utiču na svojstva zavarenog šava, a takođe zavise i od parametara zavarivanja.

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