WACKER

CREATING TOMORROW'S SOLUTIONS

ELECTROFLUX – THE SUCCESS FACTOR IN ELECTROSLAG REMELTING (ESR)

NOTHING BEATS QUALITY – CHOOSE QUALITY FROM THE MARKET LEADER

Picture: Siemens AG

Contents

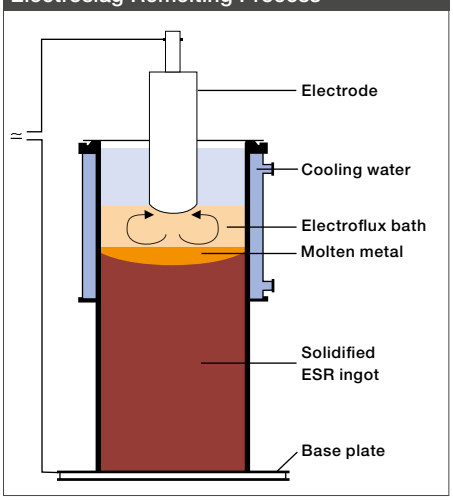
The quality of steel and nickel-base alloys depends critically on their purity and microstructure. These two properties can be optimized by refining steels and alloys in the ESR process with the assistance of Electroflux products. Companies all around the world prefer to use the high-quality Electroflux products from the market leader: WACKER.

ESR: The Key to Top-Quality Steel and Superalloys

The electrode is a cast ingot that dips into, and melts in, a resistance-heated molten bath of Electroflux. As the drops of melting metal fall through the molten Electroflux, impurities and mineral inclusions migrate from the drops into the Electroflux, and the drops are thus purified. The refined metal droplets fall into a metal sump, where they solidify at a rate controlled by a surrounding water-cooled copper mold.

ESR-refined material is free from shrinkholes and isotropic – and is characterized by high purity. As a result, ESR-refined grades offer the highest strength, longest service lives and most reliability.
ESR ingots are so homogeneous in terms of purity and microstructure that they produce markedly higher yields than is possible with steel ingots that have been cast in stationary molds.

Electroslag Remelting Process



FEWER RISKS, LOWER COSTS – PREMELTED ELECTROFLUX

Table 1: Properties of Various Grades of ESR Slags and Electroflux Products

Grade	Moisture content	Content of heavy metals*	Dust formation during handling
Premixed slag raw materials	≤ 1.5%	Bi, Pb, Cu, As, Sb, P, FeO, Fe_2O_3	Considerable
Premixed and predried slag raw materials	≤ 0.8%	Bi, Pb, Cu, As, Sb, P, FeO, Fe_2O_3	Considerable
Granulated and sintered slag raw materials	≤ 0.5%	Bi, Pb, Cu, As, Sb, P, FeO, Fe_2O_3	Little
Premelted Electroflux products	≤ 0.1%	Traces	Little
Premelted Electroflux products of ELH quality	≤ 0.006%	Traces	Little

*Commensurate with impurity levels in the raw materials

Premixed and/or predried slag raw materials, granulated and sintered slags as well as premelted Electroflux products are all commercially available. These products differ especially in their moisture content and their content of heavy metals. The best electroslag remelting results are obtained with premelted Electroflux products. Only they offer consistency of composition and constant, reproducible remelting.

Premelted Electroflux with Particularly Low Moisture Content – The ELH Series

The Electroflux products in our ELH series differ from their standard, premelted counterparts in having a moisture content which is up to 1 order of magnitude lower (ELH stands for extra low hydrogen) – this is an important property for hydrogen-sensitive steel. Their higher ratio of CaO to Al_2O_3 additionally gives them a greater desulfurization capacity than standard grades.

The Benefit of Premelted Electroflux

Although the manufacturing process adds to the cost of premelted Electroflux products, it is still worthwhile to use them. After all, the quality of an ingot produced by the ESR method depends to a considerable degree on the quality of the slag used. Using inferior slags harbors a high risk of scrappage. The potential harm far outweighs the cost of using a premelted Electroflux.

In-House Manufacture of Electroflux Products is Expensive and Risky

ESR plant operators hoping that slags melted from raw materials in-house will yield the same level of analytical consistency as Electroflux products will end up spending more on the analyses themselves than if they had purchased quality-assured Electroflux products from the start. Those who choose to ignore analyses or indeed have no access to the requisite analytical methods are taking a huge risk. Poor workpiece quality due to the use of an inferior slag during remelting can incur considerable scrappage costs and maybe even extensive legal recourse claims based on product liability. It is not without reason, therefore, that the largest manufacturers of ESR steel and alloys do not produce premelted Electroflux themselves, but rather buy in certified quality-assured Electroflux products. Using premelted Electroflux products from WACKER eliminates the following sources of error that typify in-house production from raw material components:

- Weighing errors for the raw materials
- Variable composition of the raw material components that often goes unnoticed because appropriate analytical methods are unavailable
- Undesirable carburizing of the slag during liquid start

Premelted Electroflux – Essential for Cold Starts

Modern ESR plants employ the economical cold start method. The success of cold starts is usually heavily dependent on premelted Electroflux products of suitable grain size. The cold start method with Electroflux products avoids excessive absorption of hydrogen from the moisture of the raw materials and absorption of impurities.

WACKER Offers Premelted Electroflux for Every Application

Reliable melting with modern, computer-controlled ESR plants requires products that are thermodynamically stable and whose properties do not change during remelting. Electroflux products from WACKER go a long way toward meeting this requirement. Reliable remelting of low carbon (LC) or ultra low carbon (ULC) steel and alloys calls for the use of Electroflux products with very low carbon contents. Premelted Electroflux from WACKER is suitable for this application, as well.

MANY SPECIFICATIONS, BUT THE QUALITY REMAINS THE SAME – THE GRADES IN BRIEF

Table 2: Analytical Specifications for Standard WACKER Electroflux Grades						
Grade	**% SiO_2**	**% Al_2O_3**	**% FeO**	**% TiO_2**	**% CaO**	**% MgO**
ESR 2015	1.5 ± 0.5	33.5 ± 2.5	≤ 0.2	≤ 0.2	29.5 ± 2.5	3.0 ± 1.0
ESR 2022	1.0 ± 0.5	23.0 ± 2.0	≤ 0.2		15.0 ± 2.0	2.0 ± 1.0
ESR 2027	≤ 0.5	15.0 ± 1.5	≤ 0.15	≤ 0.2	16.0 ± 2.0	≤ 1.5
ESR 2037	≤ 0.6	20.5 ± 1.5	≤ 0.15	≤ 0.2	18.0 ± 2.0	≤ 2.0
ESR 2052	≤ 0.5	≤ 1.5	≤ 0.2		≤ 2.0	
ESR 2059	≤ 0.6	22.0 ± 2.0	≤ 0.15	3.0 ± 0.6	20.0 ± 2.0	5.0 ± 0.8
ESR 2060	≤ 0.6	20.0 ± 2.0	≤ 0.2		27.0 ± 2.0	3.0 ± 1.0
ESR 2062	≤ 0.6	30.0 ± 2.0	≤ 0.15		28.0 ± 2.5	2.5 ± 1.0
ESR 2063	1.5 ± 0.5	41.5 ± 2.5	≤ 0.2	≤ 0.2	37.5 ± 2.5	4.0 ± 1.0
ESR 2065	≤ 0.8	30.0 ± 2.0	≤ 0.3	≤ 0.8	29.0 ± 2.0	≤ 1.0

Table 3: Analytical Specifications for the ELH Series of WACKER Electroflux Grades						
Grade	**% SiO_2**	**% Al_2O_3**	**% FeO**	**% TiO_2**	**% CaO**	**% MgO**
ESR 2015 ELH	≤ 0.6	32.0 ± 3.0	≤ 0.3	≤ 0.2	33.0 ± 3.0	3.5 ± 1.5
ESR 2029 ELH	≤ 0.6	30.0 ± 3.0	≤ 0.3		≤ 2.0	
ESR 2037 ELH	≤ 0.6	21.0 ± 2.5	≤ 0.3		21.0 ± 2.5	2.5 ± 1.0
ESR 3002 ELH	≤ 0.8	46.0 ± 3.0	≤ 0.3	≤ 0.2	47.0 ± 3.0	5.0 ± 2.0

% CaF_2	% H_2O (650 °C)	% C	% P	% S	% Pb	% Bi
31.5 ± 2.5	≤ 0.06*	≤ 0.06	≤ 0.005	≤ 0.04	≤ 0.005	
58.0 ± 3.0	≤ 0.06*	≤ 0.06	≤ 0.005	≤ 0.04	≤ 0.005	
67.0 ± 3.0	≤ 0.06*	≤ 0.025	≤ 0.005	≤ 0.025	≤ 0.0002	≤ 0.0002
58.0 ± 3.0	≤ 0.06*	≤ 0.025	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
≥ 97.0	≤ 0.005*	≤ 0.03	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
48.0 ± 3.0	≤ 0.06*	≤ 0.03	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
48.0 ± 3.0	≤ 0.07*	≤ 0.06	≤ 0.005	≤ 0.04	≤ 0.0002	≤ 0.0002
38.0 ± 3.0	≤ 0.06*	≤ 0.03	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
14.5 ± 1.5	≤ 0.06*	≤ 0.06	≤ 0.005	≤ 0.04	≤ 0.005	
38.5 ± 3.5	≤ 0.06*	≤ 0.03	≤ 0.01	≤ 0.03	≤ 0.001	≤ 0.001

% CaF_2	% H_2O (650 °C)	% C	% P	% S	% Pb	% Bi
30.0 ± 3.0	≤ 0.006*	≤ 0.03	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
69.0 ± 4.0	≤ 0.025*	≤ 0.015	≤ 0.002	≤ 0.015		
53.0 ± 3.0	≤ 0.006*	≤ 0.03	≤ 0.005	≤ 0.03	≤ 0.0002	≤ 0.0002
	≤ 0.005*	≤ 0.03	≤ 0.005	≤ 0.05		

* At the time of filling

GRADES BY GRAIN SIZE

Table 4: Grain Specifications for WACKER Electroflux [1]								
Grade	**Grain size**	**10 mm**	**8 mm 5/16 in**	**6.3 mm 1/4 in**	**4 mm 5 mesh**	**1.4 mm 14 mesh**	**0.3 mm 50 mesh**	**0.1 mm 140 mesh**
ESR 2022	0 – 10 mm	≤ 15		20 – 60			≥ 90	
ESR 2027	0 – 10 mm	≤ 15		20 – 60			≥ 90	
ESR 2037	0 – 10 mm	≤ 15		20 – 60			≥ 90	
ESR 2059	0 – 10 mm	≤ 15		20 – 60			≥ 90	
ESR 2015	0 – 8 mm	≤ 5	≤ 30	20 – 60			≥ 85	
ESR 2062	0 – 8 mm	≤ 5	≤ 30	20 – 60			≥ 85	
ESR 2063	0 – 8 mm	≤ 5	≤ 30	20 – 60			≥ 85	
ESR 2065	0 – 8 mm	≤ 5	≤ 30	20 – 60			≥ 85	
ESR 2052	0 – 6 mm		≤ 5	≤ 30	20 – 60		≥ 80	
ESR 2060	0.1 – 3 mm				≤ 5	20 – 60		≥ 98
ESR 2015 ELH	0 – 6 mm		≤ 5	≤ 30	20 – 60		≥ 80	
ESR 2037 ELH	0 – 6 mm		≤ 5	≤ 30	20 – 60		≥ 80	
ESR 3002 ELH	0 – 6 mm		≤ 5	≤ 30	20 – 60		≥ 80	
ESR 2029 ELH	0 – 1.2 mm					≤ 5		≥ 80

[1] % Oversize on filter in mm Mesh size (DIN ISO 3310), (mesh according to ASTM E11#)

Grain of ESR 2015

Table 5: Electrical Conductivity of WACKER Electroflux Products in Ω^{-1} cm^{-1}, Calculated According to Ogino[2]

Grade	1,700 °C	1,900 °C
ESR 2063	1.5	2.3
ESR 2015	2.3	3.0
ESR 2065	2.6	3.4
ESR 2062	2.7	3.5
ESR 2059	3.6	4.4
ESR 2022	3.7	4.5
ESR 2060	3.8	4.6
ESR 2037	4.0	4.7
ESR 2027	4.7	5.5
ESR 2052	6.5	7.3
ESR 3002 ELH	1.2	2.0
ESR 2015 ELH	2.4	3.2
ESR 2029 ELH	3.3	4.1
ESR 2037 ELH	3.8	4.6

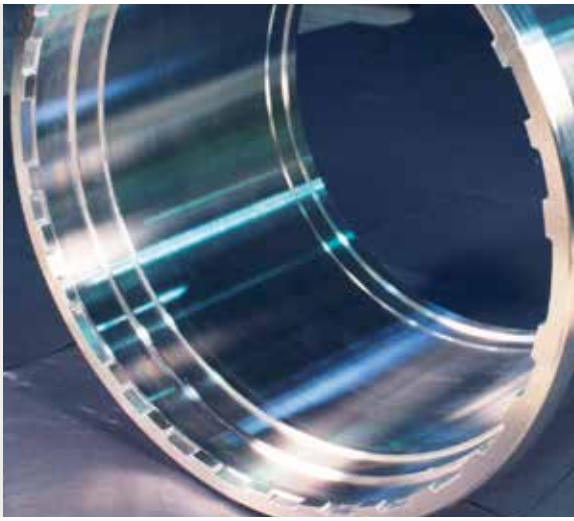
[2]K. Ogino, S. Hara, S. Nagai, Paper S, 129th ISIJ Meeting, April 1979, ISIJ Tokyo (1979)

Electrical Properties

The specific electrical resistance or the specific electrical conductivity is an important input for measuring the power consumption of Electroflux products during remelting. To enable the conductivity values of the various Electroflux products to be compared, the values were calculated according to the method of Ogino[2] and are reproduced in Table 5 for temperatures of 1,700 °C and 1,900 °C.
The values are relative.

INDIVIDUAL ADVANTAGES FOR EACH USE – APPLICATION AREAS

Picture: Merete Medical GmbH



Picture: Energietechnik Essen

Electroflux	
Grade	**Advantages**
ESR 2015	• High melting efficiency by high electrical resistance • Versatile, is therefore the most commonly employed Electroflux product
ESR 2022	• Higher conductivity and lower hygroscopicity than ESR 2015
ESR 2027	• Particularly low content of impurities in the form of SiO_2, FeO, C, S, Pb and Bi • Good desulfurization effect
ESR 2037	• Due to lower fluor-spar content, higher electrical resistance than ESR 2027, and consequently higher melting performance
ESR 2052	• Premelted fluor-spar of high purity • Only slightly hygroscopic
ESR 2059	• Contains a titanium support of 3% TiO_2. Given high Al content in the electrode, about 1% Ti in the alloy can be remelted without burn-up • Low melting point
ESR 2060	• Very high basicity, hygroscopic, low melting point • Very narrow solidification range
ESR 2062	• Similar to ESR 2015, but lower SiO_2 content and somewhat higher CaF_2 content
ESR 2063	• High Al_2O_3 content and high electrical resistance, therefore good melting performance • Despite high CaO content, only slightly hygroscopic
ESR 2065	• Similar to ESR 2015, but lower MgO content and somewhat higher CaF_2 content
ESR 2015 ELH	• Low moisture content • Particularly advantageous for melting large ingots, especially those more than 1,000 mm in diameter
ESR 2029 ELH	• Low moisture content • Extremely low content of impurities in the form of SiO_2, C, S
ESR 2037 ELH	• Particularly low moisture content • Good desulfurization effect • Advantageous melting properties
ESR 3002 ELH	• Only slightly hygroscopic, readily combinable with ESR 2052 for mixtures

Picture: ThyssenKrupp VDM GmbH

Applications	Grade
• For remelting tool steels, hot-work tool steels, stainless steels	**ESR 2015**
• For remelting structural steels, hot-work tool steels, high-speed steels as well as highly carburized tool steels	**ESR 2022**
• For remelting nickel and cobalt-base alloys and high-speed steels	**ESR 2027**
• For remelting nickel and cobalt-base alloys and high-speed steels	**ESR 2037**
• Ideal component for the production of customized compositions • Readily combinable with ESR 3002 ELH	**ESR 2052**
• Particularly suitable for remelting alloy type 718	**ESR 2059**
• For remelting Ti-containing nickel-base alloys, ball-bearing steels and steels for polished cold-rolled plates	**ESR 2060**
• For remelting tool steels, hot-work tool steels, stainless steels	**ESR 2062**
• For remelting tool steels, hot-work tool steels, e.g. glass molds, and steel strip for needles	**ESR 2063**
• For remelting nickel and cobalt-base alloys	**ESR 2065**
• For remelting tool steels, hot-work tool steels, stainless steels, due to low SiO_2 and C content, also suitable for remelting nickel-base alloys	**ESR 2015 ELH**
• For remelting nickel and cobalt-base alloys and stainless steels	**ESR 2029 ELH**
• For remelting tool steels, hot-work tool steels, stainless steels, particularly suitable for remelting large ingots of over 1,000 mm in diameter	**ESR 2037 ELH**
• For various applications, depending on mixture with ESR 2052	**ESR 3002 ELH**

ALL THE MAJOR COMPOSITIONS – FROM A SINGLE PARTNER

The Ternary System $CaO-Al_2O_3-CaF_2$, Melting Behavior

Diagrams 1 – 3 show the $CaO-Al_2O_3-CaF_2$ ternary system as described by Ries and Schwerdtfeger[3], Mitchell[4] and Nafziger[5]. Our range of products spans all the major compositions. (For plotting the slag position in the ternary system, the MgO content was included with the CaO content and the minor SiO_2 content was included with the Al_2O_3 content.)

Diagram 1 shows the isothermal cross-section at 1,600 °C according to Ries and Schwerdtfeger.

Diagram 2 shows the same ternary system according to Mitchell. Like Ries and Schwerdtfeger, Mitchell has identified the liquid/liquid miscibility gap.

Diagram 3: Nafziger did not identify this miscibility gap in his studies, and most of his melting points are lower. Nevertheless, even this diagram, with its melt isotherms, is an important indicator of the melting behavior of electro-remelt slags.

The position of the Electroflux products is indicated in each case. With the exception of ESR 2022, all Electroflux grades are found among the mono-phase stable liquids. ESR 2022 is located at the edge of the liquid/liquid miscibility gap; problems with separation phenomena rarely occur in practice.

Diagram 1: $CaO-Al_2O_3-CaF_2$ System at 1,600 °C According to Ries and Schwerdtfeger[3]

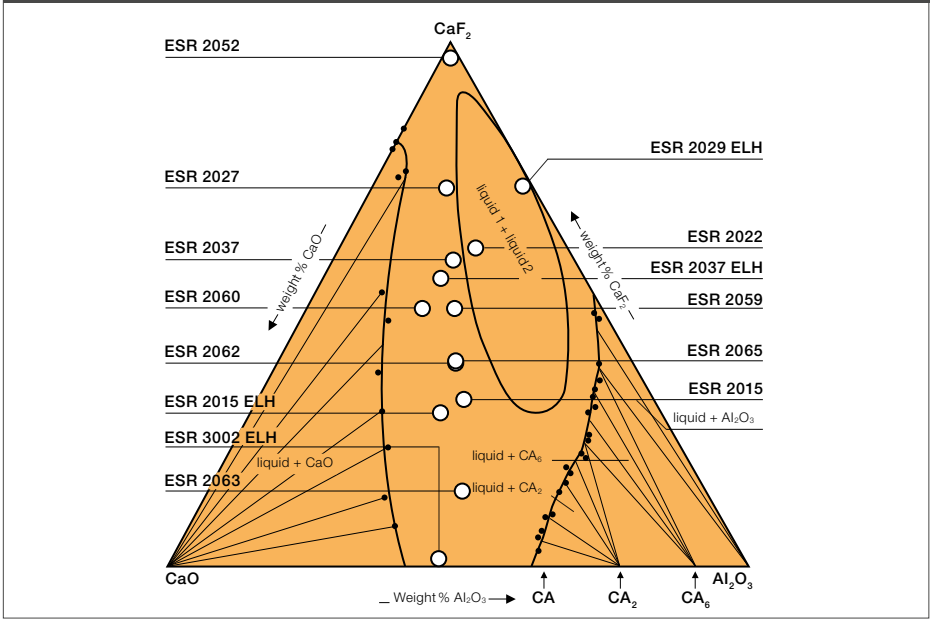


Diagram 2: $CaO-Al_2O_3-CaF_2$ System According to Mitchell[4]

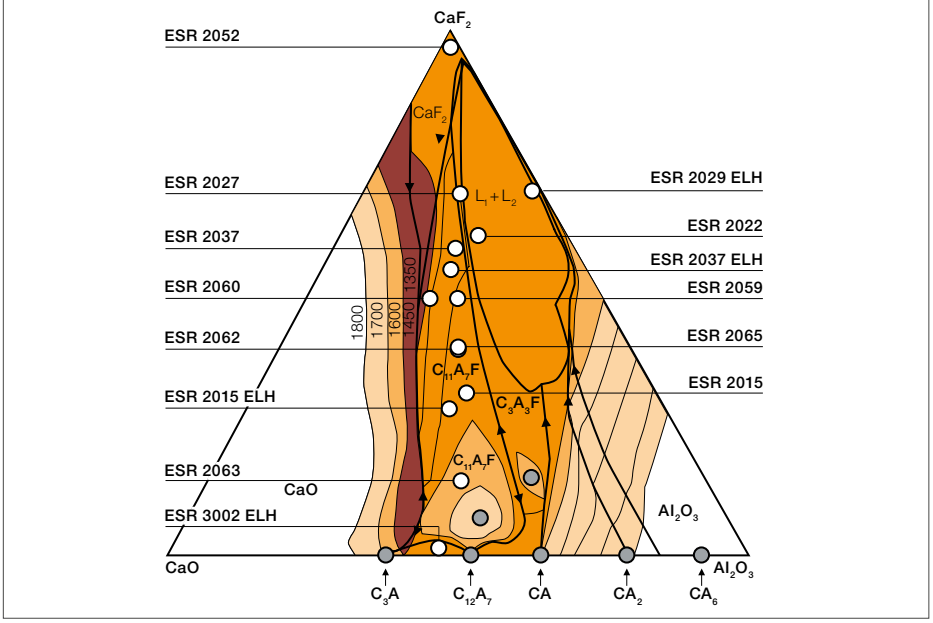


Diagram 3: $CaO\text{-}Al_2O_3\text{-}CaF_2$ System According to Nafziger[5]

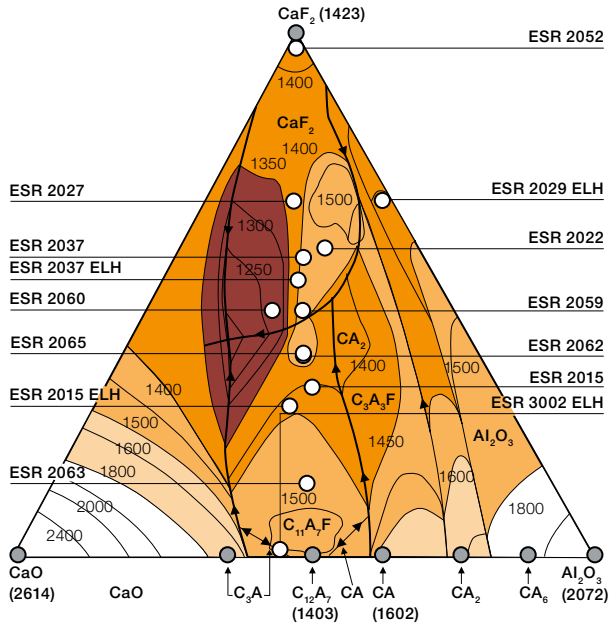


Table 6: Solidification Temperatures of WACKER Electroflux Products, Approximate Values	
Grade	**Solidification temperature**
ESR 2015	1,400 °C
ESR 2022	1,380 °C
ESR 2052	1,380 °C
ESR 2027	1,330 °C
ESR 2063	1,300 °C
ESR 2037	1,290 °C
ESR 2062	1,225 °C
ESR 2059	1,200 °C
ESR 2060	1,100 °C
ESR 2029 ELH	1,450 °C
ESR 3002 ELH	1,350 °C

Table 6 shows the approximate solidification points for Electroflux. Even though these are not precise melting point determinations, the temperatures nevertheless indicate when the respective Electroflux product turns solid on cooling.

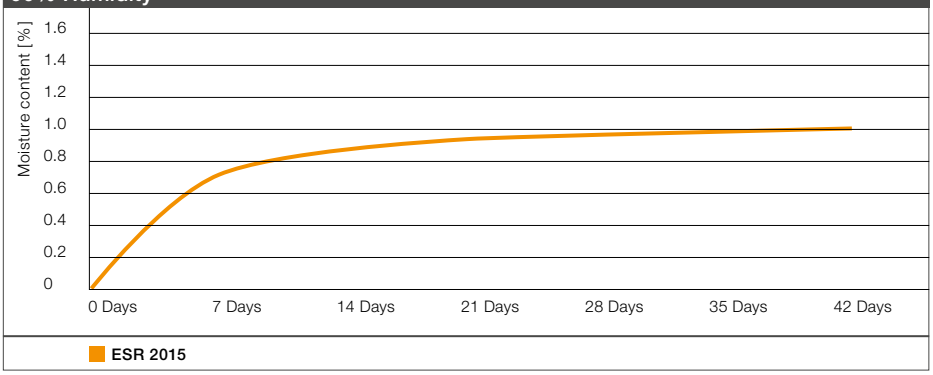
[3] R. Ries, K. Schwerdtfeger, Archiv Eisenhüttenwesen 51 (1980) pp. 123–129
[4] A. Mitchell, Canadian Metallurgical Quarterly, Vol. 20, No. 1 (1981) pp. 101–112
[5] R. Nafziger, High Temperature Science 5 (1973) pp. 414–422

PLEASE NOTE –
HANDLING INFORMATION

Storage and Shelf Life

Electroflux products are premelted products with a dense grain structure. Many of them are hygroscopic because of their CaO content. They therefore undergo hydration when stored in damp air. After an Electroflux product has been removed, the container should be sealed again immediately; the contents of opened sacks should be consumed quickly. Properly sealed containers and unopened sacks afford the best moisture protection by forming a hermetic seal that keeps moisture at bay. When these recommendations are followed, the products have an unlimited shelf life. Electroflux products stored in aluminum-coated film bags do not absorb moisture. ESR 2015 exhibited virtually constant moisture values when stored in a non-air-conditioned store room. Moisture content determined at 650 °C: 25 measurements over a period of 12 months yield readings between 0.02% and 0.03%.

Diagram 4: Moisture Content of Premelted ESR 2015 After Exposure in Air at 50 °C and 90% Humidity



Post-Drying

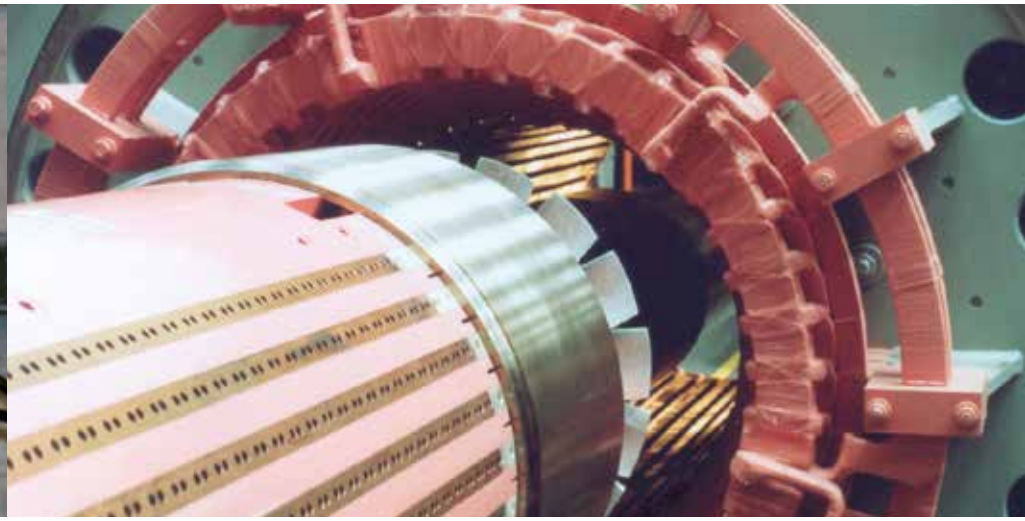
Electroflux products are normally used "as is" after delivery. During remelting of particularly hydrogen-sensitive steel and melting of very large ingot diameters, it may be best to post-dry the Electroflux products. Dry air is recommended for this. The drying temperature should be at least 700 °C, with an annealing time of 2 hours. It is advisable to fill the Electroflux products into the ESR mold immediately after the drying process and to start remelting at once.

Note

When hydrogen-sensitive steel is remelted, it should be flushed with dry air.

THE SECRET TO SUCCESS – QUALITY IS OUR WATCHWORD ...

Picture: ALD Vacuum Technologies Hanau



Picture: Energietechnik Essen

WACKER can look back on a long tradition in the development, production and marketing of premelted Electroflux products and fluxes.

The first fluxes were developed in the early 1930s. When the electroslag remelting process was first commercialized some 35 years later, Electroflux was taken up into the product range. As ladle metallurgy in steelmaking grew in importance, this was followed by synthetic premelted fluxes for steel plants.

Trend-Setting Production

A specific mixture of top-quality raw materials is melted batchwise in electrode-heated furnaces. The melt is poured into steel tubs, analyzed and, after release, is ground and screened to a specified grain size, packaged into delivery containers and readied for shipping. It is released for shipping only when all the quality controls comply with the specifications laid down in the inspection plan. Only products bearing a certificate of analysis for the respective specification are shipped. Production machines and analytical instruments are state of the art, and are operated by trained technical personnel. We have sufficient production capacity to meet market trends of the coming years.

Modern Quality Systems

WACKER is certified to ISO 9001:2008 and ISO 14001:2004.

All product workflows, from development through raw materials procurement to production and shipping, are subjected to quality assurance checks and are described in an Integrated Management System manual.

… AND SERVICE IS OUR BUSINESS

The service provided by WACKER focuses as much on quality and precision as it does on product solutions. Whether it's resource planning, technical advice or logistics issues – customers and their specific requirements are always the focal point of our service.

Security Through Flexibility

The Burghausen and Nünchritz production sites guarantee reliable, on-time delivery worldwide combined with consistently high quality. Certified raw materials sources, modern storage logistics, individual packaging units and reliable transport systems ensure punctual supply in the shortest lead times.

Added Value Through Collaboration

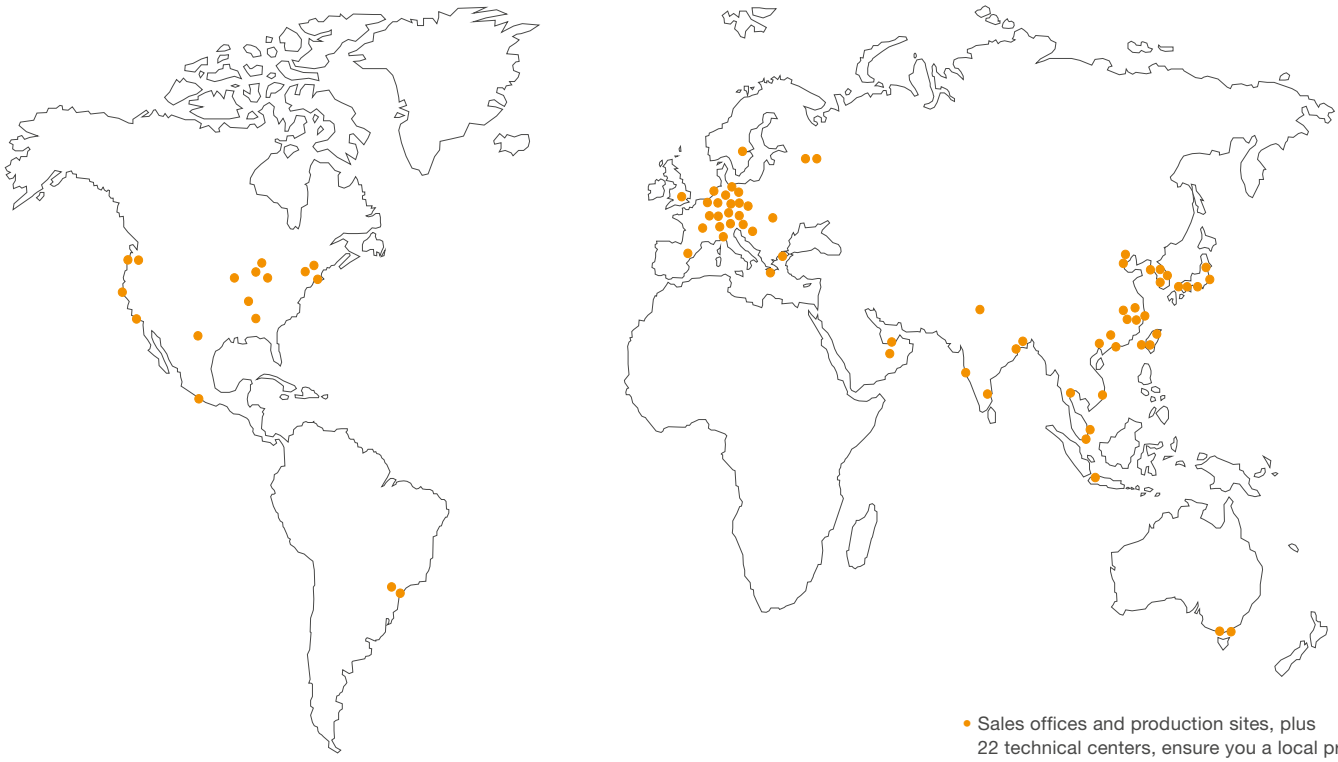
Sustainable added value is the outcome of the highest technological standards and close collaboration. WACKER offers a range of services for enhancing the effectiveness and efficiency of our collaboration with customers:

- E-Business solutions
- Vendor managed inventory (VMI)
- Supply chain management (SCM)
- Customer portal LOGIN4MORE
- SAP-SUS for procurement

The Innovative Edge

WACKER is an active member of committees around the world and collaborates closely with universities and research establishments. We are thus especially qualified to be a partner for innovations – that we will gladly initiate and see through to completion with you. Talk to us!

EXPERTISE AND SERVICE NETWORK ON FIVE CONTINENTS



• Sales offices and production sites, plus 22 technical centers, ensure you a local presence worldwide.

WACKER is one of the world's leading and most research-intensive chemical companies, with total sales of €5.3 billion. Products range from silicones, binders and polymer additives for diverse industrial sectors to bioengineered pharmaceutical actives and hyperpure silicon for semiconductor and solar applications. As a technology leader focusing on sustainability, WACKER promotes products and ideas that offer a high value-added potential to ensure that current and future generations enjoy a better quality of life based on energy efficiency and protection of the climate and environment.

Spanning the globe with 5 business divisions, we offer our customers highly-specialized products and comprehensive service via 25 production sites, 22 technical competence centers, 12 WACKER ACADEMY training centers and 50 sales offices in Europe, North and South America, and Asia – including a presence in China. With a workforce of some 17,000, we see ourselves as a reliable innovation partner that develops trailblazing solutions for, and in collaboration with, our customers. We also help them boost their own success. Our technical centers employ local specialists who assist customers worldwide in the development of products tailored to regional demands, supporting them during every stage of their complex production processes, if required. WACKER e-solutions are online services provided via our customer portal and as integrated process solutions. Our customers and business partners thus benefit from comprehensive information and reliable service to enable projects and orders to be handled fast, reliably and highly efficiently. Visit us anywhere, anytime around the world at: **www.wacker.com**

All figures are based on fiscal 2015.

WACKER

Wacker Chemie AG
Johannes-Hess-Strasse 24
84489 Burghausen, Germany
Tel: +49 8677 83-0
Fax: +49 8677 83-3100
info.burghausen@wacker.com

www.wacker.com/socialmedia

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