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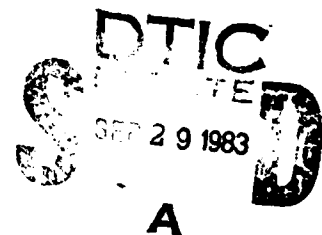NATIONAL BUREAU OF STANDARDS-1963-A

MRL-R-879

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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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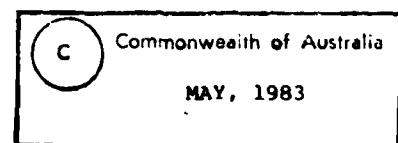
REPORT

MRL-R-879

ESR STEELS FOR DEFENCE

- STATE OF THE ART

MRL Seminar,

December 14, 1982

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ESR STEELS FOR DEFENCE - START OF THE ART, MRL SEMINAR,
DECEMBER 14, 1982

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	Electroslag refining	Armour
	ESR steels	Welding
	Fracture	Machining
	Fatigue	Corrosion

COSATI GROUPS   1106

ABSTRACT

A seminar was conducted at MRL at which various speakers gave presentations on the state of the art in defence uses of ESR steels. The ESR process was described and the local manufacturing facilities were detailed. The fatigue, fracture, weldability, machining and corrosion properties of ESR steels were outlined, and the applications of ESR steels to the manufacture of armour and munitions were discussed.

ESR STEELS FOR DEFENCE

-   STATE OF THE ART

December 14, 1982

A summary of a One-Day Seminar sponsored

by Metallurgy Division,

Materials Research Laboratories

C O N T E N T S

ESR STEELS FOR DEFENCE

STATE OF THE ART

Maurice de Morton
A/Superintendent, Metallurgy Division, MRL

By way of introduction to this seminar I would like to read to you two quotations:

"If our experience is any criterion, the day is not far off when all high-performance steels and alloys will be electroslag refined".

and the second quotation

"The MOD* results show that the use of ESR steels does not necessarily mean that an improved product with a high ingot yield will be achieved. Results on ESR gun steels demonstrate that, for optimum properties, careful process control must be exercised otherwise properties and ingot yield may be lower than anticipated."

* Ministry of Defence, UK

The first quotation was made in 1972 by the Manager of Cabot Corporation, US Steelmakers. The second in 1982 from a UK MOD, R and D authority. What do we conclude from these seemingly contradictory statements and what is their relevance to Australian production of ESR steel? Are promises made for ESR steels diminishing with time as more detailed trials are completed? Or are we comparing apples and pears?

This seminar was in fact prompted by the following proposition. If ESR steels are so good and we have a commercial capability in Australia, why are we not using more for Defence equipment? After all, Defence needs for high quality, high performance materials probably surpass all others. Aircraft, guns, armour, ships, submarines, critical vehicle components must all be prime candidates for premium quality materials.

When we spoke with interested people about ESR steels we found some enlightened and some confused, while others had unique and specialized experience with ESR that had very limited circulation. If this seminar acts as a catalyst to bring out these views I believe it will be worthwhile.

For the remainder of this introduction I would like to look briefly at the following aspects of ESR materials:

(i)   Why we need quality.

(ii) How we get it.

(iii) What we pay for it.

Why we need quality

The history of steelmaking is indeed a very long learning curve, mainly by trial and error.   Only relatively recently has there been any scientific input.   The period where the technology was pushed by alloy development has been overtaken by the pull of process improvements of existing alloys for better quality at reduced cost.   The ESR process falls squarely into this category.   In this sense quality is synonymous with performance - we define one in terms of the other.

In Defence we need materials to withstand high stresses, particularly at high loading rates, and yet remain tough and ductile.   The degradation of materials by alternating load cycles in particular is to be resisted.   Foremost is the requirement for uniformity of properties throughout the material and from heat to heat.   I believe that we will find this to be one of the most important requirements.

Graham Clark and Ray Woodward will be discussing how uniformity of composition and residual impurities affect the fracture and ballistic properties of steels.

How We Get Quality

Techniques for the improvement of steel quality usually involve remelting - the so-called secondary steelmaking processes.   These processes are shown sequentially in Fig. 1 : high carbon pig iron from the blast furnace is charged into a large ladle, together with scrap and the excess carbon burnt off by oxygen blown through the melt.   This is the basic oxygen process. For higher performance steels, scrap from the basic oxygen processes is remelted in an electric arc furnace, together with ferro-alloys to produce stronger alloys.   These alloys in turn are further refined by the ESR or VAR process.   The ESR process will be detailed by John Ritter in the next talk.

Let me briefly say what VAR (vacuum arc refined) steel is although we do not have VAR units in Australia.   The process is as follows.   A steel electrode of about the required composition is drip-melted, by arc-heating, into a water-cooled copper mould, in vacuo as shown in Fig. 2.   Induction heating may also be used.   The process produces very sound ingots with low hydrogen and oxygen contents and minimal segregation of elements and non-metallic inclusions.

Now returning to the ESR process. The Soviets pioneered the ESR process in the 1930's, long before the USA and Europe, and have exploited the properties, particularly in the "as cast" condition. The USA invested heavily in the capital equipment necessary for VAR and VIM processes and, because of this, delayed introduction of ESR plants. As our first quotation indicated this has now changed.

The first ESR steel made in Australia was made here at MRL in a small experimental unit in 1974. A commercial unit with a capacity for 34 tonnes was commissioned by Comsteel in Newcastle in 1979 and we are pleased that Graham Ormerod will be describing this work today. We are also pleased to say that MRL was also involved in the early operation of this commercial unit.

Ordnance Factory Maribyrnong has also had a long and sustained interest in the use of ESR steels and we are pleased to have Bill Cosgrove to discuss OFM's experience in forging, heat treatment and machining ESR material. Successful welding, machining and resistance to corrosion of steels is heavily dependent on the distribution of non-metallic inclusions and these aspects of ESR steel will be discussed by Bob Phillips, Derry Doyle and Russell Taylor.

What we pay for it

In theory the cost of the power consumed in the remelting of ESR steel is offset against reduced cropping of the ingot due to a reduction in shrinkage defects and lower forging reductions due to better uniformity of composition and structure. The second quotation indicates that the offsets have not been fully realized, at least in the UK, and I am sure we will hear more about this important aspect today.

Finally, what we in Defence have to face up to is that we are very small users of steel and this puts us at a distinct cost and priority disadvantage. The same is true of the USA but not necessarily of the UK where an ESR plant has been set up in at least one Government factory. A projection, made in 1975, for the likely quantity of ESR steel required for Defence use in 1982 was 300-550 tons. I suspect that actual Defence usage fell well short of this estimate.

We have represented here today steelmakers, design engineers, production engineers, R and D and end users. With some very large Defence projects in the offing I believe the time is indeed opportune for this forum and I look forward to some healthy and enlightening discussion.
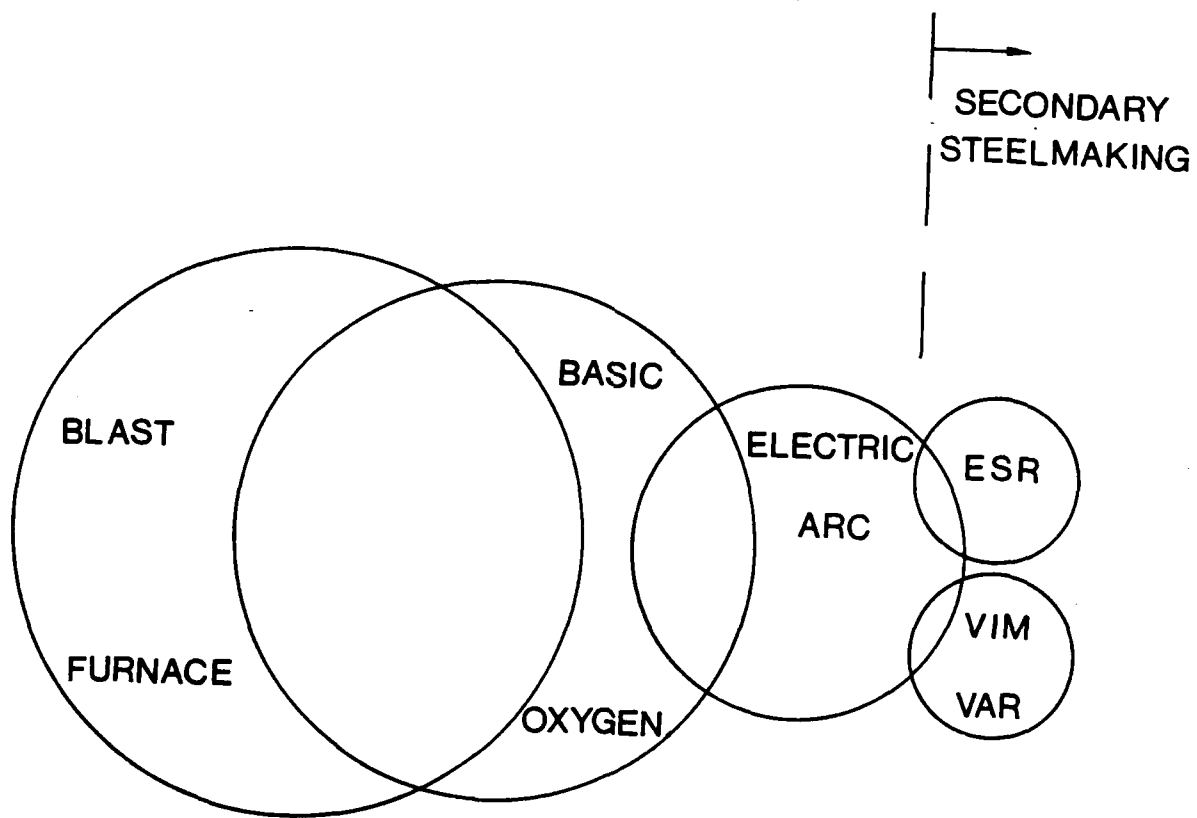
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FIG 1   The Route to ESR and VAR Steels

TO POWER
SOURCE

TANK
TOP

CONSUMABLE
ELECTRODE

VACUUM
PUMP

LIQUID
STEEL

SOLID
STEEL

WATER-COOLED
COPPER MOULD
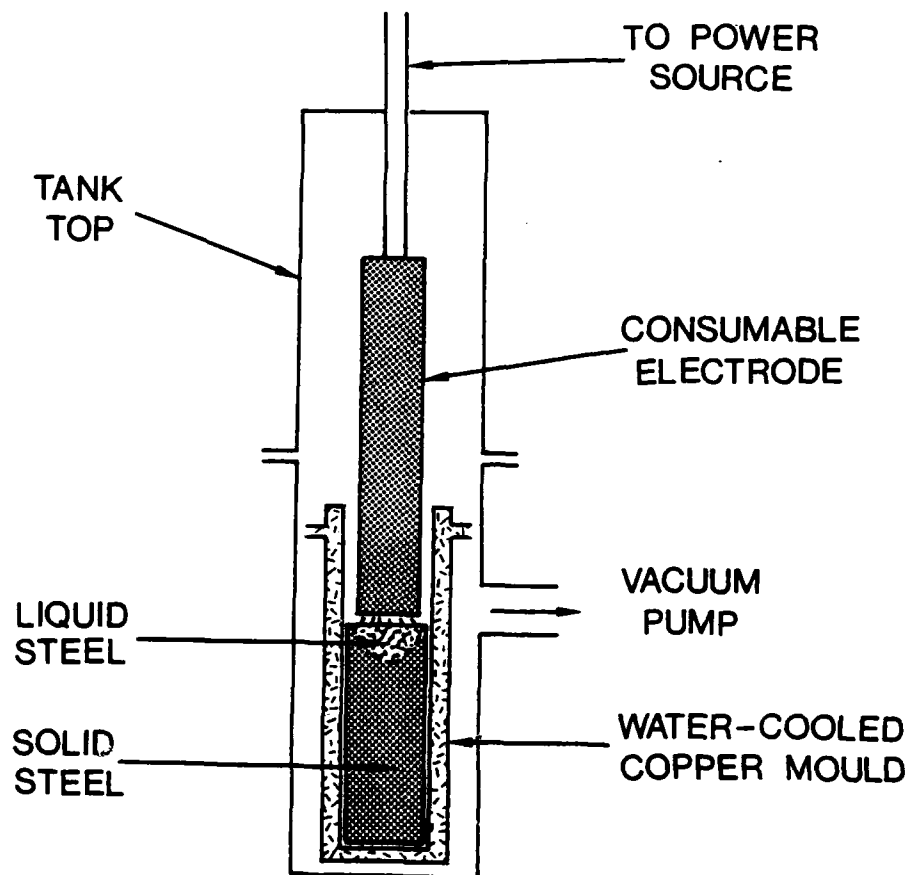
FIG 2   Vacuum Arc Refined (VAR) Process

<u>THE ESR PROCESS</u>

John Ritter, MRL

        This contribution aims to describe the process and what it does, to
compare it with competing processes, and indicate the improvements in
mechanical properties of premium quality steels which can be expected of the
process.

THE PROCESS

        ESR is commonly referred to as Electroslag Refining or Remelting
depending upon one's viewpoint, and is synonymous with the older term
Electroflux Refining.

        It is a secondary refining process, shown schematically in the
diagram.   The solid feedstock is steel of the final composition in alloying
elements and cast or wrought into a consumable electrode.   Under a high-
current, low-voltage power supply the electrode is dipped into a bath of
molten, conducting slag contained in a water-cooled mould.   When the current
is sufficient to raise the slag temperature above the melting point of the
electrode, molten droplets fall from the tip of the electrode, through the
superheated slag, to form a small pool at the base of the mould.   The
electrode is progressively fed into the slag bath and an ingot builds up in
the mould.
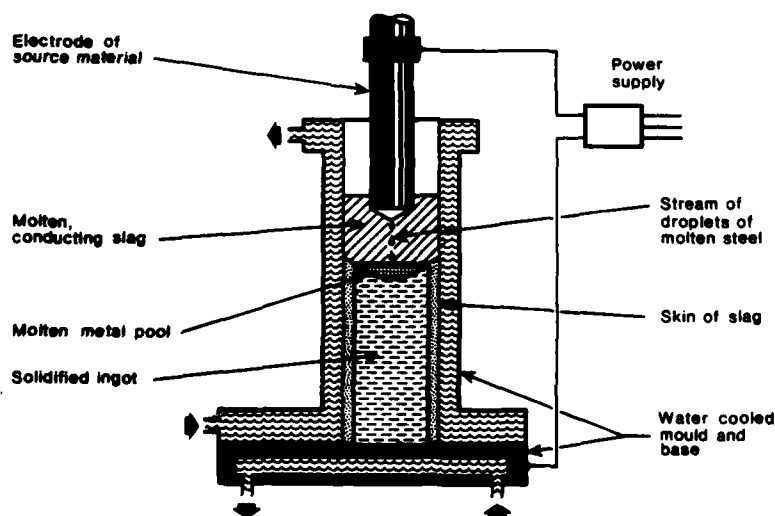
Progressive solidification of this small, shallow pool in a near-axial direction ensures a sound ingot, free from porosity and centreline macrosegregation which, in turn, reduces the amount of microsegregation. Local solidification is markedly faster than in conventionally cast ingots of similar size - where the whole ingot is poured and then allowed to solidify - resulting in a finer solidification pattern. The slag bath can act as a hot-top at the completion of remelting, and provide a small increase in ingot yield.

Chemical refining occurs during all stages of contact between molten metal and slag. The slag itself, usually composed of CaF_2, CaO and Al_2O_3 with additions of SiO_2 and MgO in pre-determined proportions, serves other functions besides the resistance heating unique to ESR: chemical reaction can remove sulphur to a large degree and retain oxidizable alloying elements; the presence of a continuous film of solidified slag at the mould surface can give excellent surface finish on the ingot. Forced dry air circulation above the slag bath can assist desulphurization and keep ingot hydrogen to a low level. The use of a metal mould eliminates a common source of refractory pick-up.

COMPARISON WITH OTHER SECONDARY REFINING PROCESSES

Nowadays there are many variations of secondary refining processes available involving vacuum degassing, injection of gases and addition of refining elements; nearly all are done to a vessel of molten metal. The important feature which takes ESR beyond all of these processes is that a very small amount of steel is molten at any given instant, so achieving the important advantage of a fine, nearly homogeneous solidification pattern. It scores over its remaining rival for tonnage steels, vacuum arc remelting (VAR) because the presence of a molten slag layer allows greater process control and chemical refining (e.g. desulphurization) than is possible in vacuo. VAR removes oxygen, nitrogen and hydrogen directly, and oxidizable alloying elements are not threatened, but the intense arc transfer from electrode to ingot can lead to loss of volatile elements. Improvement in steel cleanliness can be greater by ESR than VAR, but not always.

Both ESR and VAR add significantly to the cost of the final product, VAR perhaps more so. Cost penalty in ESR is exacerbated by the need for low rates of remelting ($\sim$ 500 kg/h in practice) to preserve the special solidification conditions, but is eased somewhat by the higher ingot yield. ESR offers greater flexibility of melting rate, the use of multiple electrodes, wider process control through varying slags, and a variety of end products using moving and specially shaped moulds.

PROPERTIES OF ESR STEELS

Consideration is given to the high-strength, quenched and tempered steels of the En 25/AISI 4340 type used in ordnance manufacture. The unique combination of chemical and microstructural refinement of the ESR process can be used to achieve significant improvements in the fatigue strength and fracture toughness of these steels.

Good refining practice will achieve an as-cast microstructure which is close to homogeneous and is free from microporosity. Given due care, subsequent heat treatment can produce a steel with very high, uniform properties even on a microscopic scale, a matter of considerable shortfall in conventional ingots which requires them to be extensively hot worked. Good ESR ingots will have a very low level of non-metallic inclusions, particularly sulphides and also oxides; those present will be very fine particles (~ 10 μm diameter) uniformly dispersed, quite unlike the coarse particles in conventional ingots which break down into harmful stringers during hot working. The mechanical properties of as-cast ESR steels therefore tend to be highly isotropic. Invariably, there is a close link between the improvement in mechanical properties obtained by ESR and the extent of desulphurization achieved in the refining process.

Elimination of the coarse non-metallic particles removes the primary sites for easy initiation of ductile overload fracture and of rapid jumps in fatigue crack propagation. Consequently, the fracture toughness and fatigue resistance of as-cast ESR steel can fully match those of wrought electric furnace steel in the limiting short transverse direction, opening up real prospects for using as-cast ESR steel even in critical applications. Currently overseas, a trial batch of cast large calibre gun barrels is being evaluated against conventionally forged ones.

Upon hot working of ESR ingots, the mechanical properties tend to show a small improvement, although some or all may undergo a localized dip at forging ratios around 1.5 to 1. The reason for this behaviour is not yet understood.

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ELECTROSLAG REFINING AT COMSTEEL

Graham Ormerod, Comsteel

1. INTRODUCTION

An electroslag refining plant was commissioned at Comsteel's Waratah
plant in February 1979.   The unit was manufactured by the Consarc Corporation
of the USA and was chosen on its ability to produce ESR feed ingots for a wide
range of product types and sizes including forgings, bar products and rolled
plate and strip.

2. PLANT DESCRIPTION

2.1 General

The unit comprises three melting stations and two furnace heads.
Static melting may be carried out simultaneously in any station for ingots up
to 800 mm ϕ or in a single station for ingots up to 1100 mm ϕ.   The centre
station is also designed to produce ingots using the ingot withdrawal method
with electrode change technique, the largest ingot size possible being
1100 mm ϕ weighing 33.5 tonne.   Capacity of the unit is 7000 t.p.a.

2.2 Power

Melting power is provided by two 25,000 ampere AC power sources.   A
parallel bus-bar interlock is available to operate both power sources on any
one melting station, this facility being required for the larger melts.

2.3 Ancillary Equipment

The plant is equipped with a number of ancillary units which
incorporate the latest technologies for improved performance.

2.3.1 Molten Slag Arc Furnace

A 700 kg capacity graphite lined arc furnace is used to prefuse slag
charges adjacent to the remelting stations, allowing faster operation of the
plant.

2.3.2 Dry Air Supply

To avoid hydrogen pick-up, all slag surfaces whether molten or solid
require the protection of a dry air atmosphere.   Dry air from the
dehumidification plant is forced over the molten slag layer during remelting
using a baffle system on top of the crucible.   The dry air is also used
during slag component storage and slag prefusing.

2.3.3 Automatic Melt Rate Control

A major feature of the installation is the fully automatic melt rate control system. Changes in electrode mass, as determined by load cells mounted on the electrode heads, are relayed via interface units to microprocessors which determine melt rates. The processors adjust melting currents so that predetermined melt rates are maintained. The processors also control the hot topping sequence at the end of remelting.

2.3.4 Alloy and Slag Feeder Units

Portable units are available to allow controlled additions of alloys, slags and deoxidants during remelting. The melt rate control system is used to meter levels of addition at the required rate.

3. PROCESS PARAMETERS

3.1 Electrodes

The majority of electrodes for remelting are produced as conventional bottom poured ingots from electric arc furnace vacuum degassed steel. The ingot is designed to provide the correct fill ratio for remelting.

3.2 Melt Rate

The attainment of a uniform ingot structure during remelting for any given electrode fill ratio is largely determined by the liquid pool depth, which is related essentially to the melt rate. For productivity reasons it is an extremely important aspect of the operation to achieve maximum melting rates for each material grade and ingot size consistent with the required material quality level. The application of the automated melt-rate control facilities to pre-programme a melt rate cycle which does not require operator attention enables consistently reproducible melts at optimum rates. In the initial stages of production, considerable evaluation of pool depths and solidification features was carried out to establish optimum melt rates.

3.3 Slag and Deoxidant Systems

Since commissioning of the plant, a series of large scale evaluation programmes have been conducted with the joint participation of the Materials Research Laboratories, Maribyrnong, to examine slag and deoxidation practice. The influence of numerous slag/deoxidant systems on the ESR ingot surface condition, the electrode to ingot chemical composition changes occurring during refining, the inclusion frequency, size and morphology and the subsequent mechanical, fatigue and fracture toughness properties for various grades of alloy steels have been examined. These results allow the selection of appropriate slags and deoxidants for a specific application.

4. PRODUCT RANGE

The range of ESR steels produced by Comsteel covers roll steels, tool steels and low alloy engineering steels. The roll steel is a carbon chromium grade used for the manufacture of cold rolling mill work rolls for tin plate manufacture. There is interest in using this material for rolls in the aluminium foil industry, replacing VAR material. Many of the tool steel grades marketed by Comsteel now include electro-slag refining in the standard manufacturing process. These include hot work, cold work and plastic moulding die steels. Benefits both to the manufacturer and user are evident. The low alloy engineering steel group are widely used in mining and ordnance applications. The use of remelt quality steels for key components in the mining industry is aimed at reducing or eliminating many costly failures and the frequent routine replacement of critical parts. Applications include slew bearing components and swing shafting for dragline machinery and heavily loaded gears and shafting for a variety of mining equipment.

On the ordnance side, ESR feed or finished components have been supplied for the following:-

- Ni Cr Mo breech blocks for Watervliet Arsenal.
- En25 rifle barrel steel.
- a line shaft, the smallest of the three shafts that make up the propulsion shafting on the FFG Frigates, and a rudderstock.

- Ni Cr Mo V steel for mortar barrel production.
- 4340, 630 grade precipitation hardening stainless steel and AISI H11 material for the production of civil aircraft components.
- nitrogen strengthened, micro alloyed austenitic stainless steel propeller shafting for the Australian Fremantle Class Patrol Boats.
- 4340 barstock for the manufacture of brake components for the F18 fighter.

Future Development

Future development work on ESR steels will be carried out in conjunction with a Department of Defence Support R & D contract to study electroslag remelting of three premium quality alloys, namely,

- 4340 grade in 800 mm ϕ ESR ingots to supplement previous work on the smaller 380 mm square ingot size,
- 300 M grade high strength low alloy steel, and
- Alloy A286, a precipitation hardening, corrosion and heat resisting steel.

Traditionally, these steels have been produced by vacuum remelt

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methods. The purpose of this work will be to establish ESR practices suitable for manufacturing material to meet the relevant military specifications.

CONCLUSION

The facilities and technology are available in Australia for the production of premium quality ESR alloy steels suitable for use in many ordnance and general engineering applications.

QUESTIONS

Q: Is hydrogen contamination a problem in the ESR process?

A: The hydrogen can be sampled during the time it takes for the electrode to be changed (approx 45 secs) and the hydrogen pickup is generally $< \frac{1}{2}$ ppm.

Q: Considering the directional solidification of the ESR ingot, how does the directionality of the plate in rolling affect its properties?

A: The plate has improved anisotropy, and the lower number of inclusions leads to better properties.

Q: Have you any comments on machinability problems of SAE-AISI-304 (ESR stainless) steels?

A: The 304 grade steels are always difficult to machine, and this is not dependent on the ESR process, but the ESR steels do show a hot workability gain, improved cleanliness and reduced inclusions.

Q: Is there a carbon build-up in the slag?

A: The slag is pre-fused in a carbon-lined crucible, so the time the slag is retained must be limited. Any carbon picked up is normally confined to the bottom end of the ingot, and so there is a minimal amount of discard. In one instance, chemical analysis did reveal an unexplained variation in the amount of carbon between electrode and ingot. However, this has not recurred.

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ESR STEELS FOR DEFENCE

Bill Cosgrove, OFM

Ordnance Factory Maribyrnong first became involved with production of defence stores from ESR steel in August 1979. We won the contract for supply to the USA of two hundred breechblock forgings for the 155 mm M198 howitzer.

Reasons for selecting ESR steel

(1) We were exporting black heat treated forgings which would be machined some time in the future and would then be subjected to a critical magnetic particle examination. We had to be confident of the steel cleanliness and that any non-metallic inclusions would be small and widely distributed.

(2) At quite high strength levels a high impact strength was required. We were more confident of meeting these requirements using ESR steel.

A total of five heats of ESR steel, approximately 30 tonnes, was used to complete the 200 forgings. The required composition, MIL-S-46172/C, and two typical heat analysis results, Z209 and Z211, are shown in table 1.

Z209 and Z211 were each 800 mm diameter 12 tonne ESR ingots. Each ESR ingot is the product of one electric furnace steel ingot after remelting, the two EF ingots being poured from one heat. Note the homogeneity between the top end and bottom end of each ingot and the reproducibility of composition between successive heats. Also note the very low sulphur levels.

The ESR ingots were forged into barstock, the barstock sawn into billets and the billets upset drop forged to produce the breechblocks themselves. After heat treatment the mechanical properties which were obtained are shown in table 2. Note the high ductility and very high impact strength results, both are well above specification requirements. Magnetic particle examination of the breechblocks after finish machining in the USA did not lead to any rejects.

The only other major project at OFM which has employed ESR steel is one which is currently underway, the manufacture of one hundred 81 mm mortars. The mortar barrels are being manufactured from ESR steel for the first time; many hundreds of similar barrels have been made in the past from electric furnace steel. The barrel material was purchased as rolled barstock. The barstock is rough machined, heat treated, mechanical tested and then finish machined to produce a barrel.

At the moment there are only 16 ESR barrels through mechanical testing. The 16 ESR barrels and 16 of the last electric furnace steel barrels produced are compared in table 3.

The chemical analyses of the two steels being compared in table 3 are important and must qualify any conclusions drawn as to the mechanical properties of the two steels. We would expect the higher carbon material to have a lower impact strength at a given proof stress. However, it must also be remembered that both of these steels were supplied to fulfill a contract requirement to meet certain mechanical properties as well as a chemical composition range. In fact the ESR heat is too high in carbon, but was accepted because it is still capable of obtaining the required mechanical properties. Whether or not the application of the ESR process has caused the error in chemical composition we do not know, but from the final mechanical properties obtained it is clear that in this particular project the use of ESR steel has not offered any advantages at all. The use of ESR steel could be justified if we obtained a significantly lower loss rate at the final magnetic particle examination after finish machining. However, the micro-examination and inclusion content rating tests applied so far do not show this ESR heat to be significantly better than a good grade of vacuum degassed electric furnace steel.

Summary of differences observed in the processing of ESR and electric furnace steels:

1. Forging

The very low sulphur content of ESR steels makes them more susceptible than similar electric furnace steels to overheating. In order to obtain the maximum impact strength of an ESR forging, it may be necessary to reduce the forging temperature. A reduction in forging temperature results in poorer forgability and increased die wear.

2. Turning

Turning operations have shown that there is a tendency for ESR swarf to be produced as strings rather than chips. We have also observed a small decrease in tool life when turning ESR steels of composition similar to electric furnace steels.

3. Drilling

Ejector drilling operations are severely disadvantaged by the tendency of ESR steel to not form chips when machined. When we first commenced ejector drilling the bore of ESR 81 mm mortar barrels, we used the same tools as had been used successfully before. We immediately observed a tool life of approximately one tenth that expected. Modification of the chip breaker geometry has improved the tool life considerably but it is still only approximately half that expected.

Conclusions

1. High quality ESR steel possesses greater ductility and greater impact strength than high quality electric furnace steel is capable of obtaining, at a given strength level.

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2. The ESR steel used at OFM to date has been generally comparable to good grades of vacuum degassed electric furnace steel or better, but is variable in cleanliness and transverse impact strength.
3. ESR steel costs more to process than does electric furnace steel and is more expensive to purchase.
4. In general, OFM cannot justify the added costs of using ESR steel for gun and rocket motor forgings and will continue to use high quality vacuum degassed electric furnace steel.
5. Perhaps the next generation of guns and rocket motors will be designed to utilize the higher ductility and impact strength which can be obtained using secondary refining processes such as ESR. Until then electric furnace steel will remain highly competitive for use in highly stressed defence components.

Comment from the floor

There is no justification for using the lower soak temperature during drop forging (1150°C vs 1200°C) which you remark leads to high die wear. Firstly, soak temperatures above 1250°C are required before overheating starts to influence properties, and secondly, because forging operations are normally carried out after soaking, any overheated boundaries that were formed would be broken up. A problem might rise, therefore, if clean steels were soaked at temperatures approaching 1300°C without hotworking. However, even under these unusual circumstances, because the strength of a clean ESR steel usually greatly exceeds specification, a small loss of strength may not matter.

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T A B L E 1

CHEMICAL COMPOSITION

	MIL-S-46172/C		Z209		Z211	
	Min.	Max.	Top end	Bottom end	Top end	Bottom end
C	0.28	0.33	0.30	0.31	0.30	0.30
Mn	0.50	0.90	0.65	0.63	0.63	0.63
Si	0.15	0.35	0.32	0.29	0.25	0.30
P		0.015	0.014	0.014	0.014	0.014
S		0.015	0.007	0.006	0.009	0.004
Ni	2.20	2.50	2.36	2.38	2.40	2.33
Cr	0.80	1.20	0.92	0.91	0.91	0.92
Mo	0.40	0.80	0.60	0.60	0.60	0.61
V	0.08	0.15	0.12	0.12	0.12	0.12

All values are weight percent.

T A B L E 2

MECHANICAL TEST RESULTS ON 155 mm BREECH BLOCKS

	0.1% Proof Stress (kpsi)	U.T.S. (kpsi)	Fracture	Elongation in 2" (%)	Reduction of Area (%)	Charpy 'V' -40°C (ft.lbf)
Z209 A	159	170	Cup	18	55	47
B	158	170	Cup	18	56	40
Z211 A	158	168	Cup	18	56	49
B	158	168	Cup	18	57	51
Lowest Strength[a]	154	167	Cup	19	57	51
Highest Strength[a]	165	177	Cup	18	55	39
Acceptance Require- ments[a]	150-159	-	-	-	30 min.	20 min.
	160-169	-	-	-	25 min.	15 min.

Notes: (a) Values over all five heats (about 40 tests overall).
        (b) Reduction of Area and Impact requirements vary with Proof stress range.

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T A B L E   3

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF 81 mm MORTAR BARREL MATERIALS

A   Vacuum Degassed Electric Furnace Steel

Chemical Analysis (Wt %)	C	Mn	Si	P	S	Ni	Cr	Mo	V
	0.39	0.41	0.69	0.010	0.007	1.79	1.60	1.07	0.25

Mechanical Properties of a Typical Barrel

	0.2% Proof Stress (MPa)	U.T.S. (MPa)	Elongation (%)	Reduction of Area (%)	Charpy 'V' -40°C (J)
Top end	1460	1625	10	37	11, 10
Bottom end	1490	1655	10	36	11, 8

Impact Properties of 16 No. Barrels (64 No. Impact Tests)

Highest impact value   13.5 J
Lowest   "   "   8   J
Average   "   "   10.7 J

B   ESR

Chemical Analysis (Wt %)	C	Mn	Si	P	S	Ni	Cr	Mo	V
	0.49	0.37	0.78	0.008	0.007	1.95	1.45	0.91	0.27

Mechanical Properties of a Typical Barrel

	0.2% Proof Stress (MPa)	U.T.S. (MPa)	Elongation (%)	Reduction of Area (%)	Charpy 'V' -40°C (J)
Top end	1543	1604	12	36	11, 10
Bottom end	1477	1677	10	34	11, 8

Impact Properties of 16 No. Barrels (64 No. Impact Tests)

Highest impact value   13   J
Lowest   "   "   8   J
Average   "   "   10.5 J

FRACTURE AND FATIGUE OF ESR STEELS

Graham Clark, MRL

A major benefit of electroslag refining arises from the increased
fracture toughness of the forged ESR ingot compared with the steel used as
feedstock. This increase can arise from any of a number of metallurgical
changes, not all of which, however, need occur in any particular case:

(i)   reduction in macrosegregation of alloy and impurity elements
(ii)   reduction in total non-metallic inclusion content
(iii)   redistribution of non-metallics - large particles and stringers
        eliminated, distribution biased towards smaller inclusion sizes
(iv)   refinement of microstructure.

Routine mechanical testing of small specimens, intended to check the
material's compliance with specification, will be influenced by each of these
changes. The safety and reliability of highly-stressed components, however,
is particularly sensitive to the presence of the largest non-metallics, which
may not be revealed in small specimen tests.

Assessments of the effects of ESR processing on safety and
reliability therefore require bulk material inspection techniques, as well as
routine mechanical testing.

Two aspects of fatigue and fracture of ESR steels are discussed
below:

1. AS-CAST ESR LOW ALLOY STEEL

The use of ESR casting for the manufacture of components with
complex shapes offers considerable benefits, by reducing (or eliminating) the
time and cost of subsequent forging and machining operations. However, for
satisfactory results, the as-cast component must have similar properties to
more conventional forged components.

An MRL investigation comparing the impact and fatigue properties of
as-cast ESR En 25 steel ingots with those of the wrought commercial En 25
feedstock material is described in report MRL-R-786. Both materials were
heat treated. Notch impact toughness results obtained using Charpy V-notch
testing (Fig. 1) indicate that:

(i)   Longitudinal (L) and transverse (T) properties of the ESR material
        are similar to the T properties of the wrought material.
(ii)   The L properties of the wrought material are superior to all other
        conditions tested.

This behaviour was confirmed using larger fracture toughness
specimens. Figure 2 compares the fatigue-crack growth properties of the same
as-cast ESR and wrought EF steels. Over the range of stress-intensities

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used, the T orientations of both materials displayed the same fatigue crack growth rates, and these data lay within the experimental scatter of tests in L orientations.

In many applications, the use of wrought material is limited by its relatively poor properties in the transverse direction, and these impact and fatigue results indicate that after heat treatment, as-cast ESR material could be a suitable alternative with the possible advantage of reduced manufacturing costs.

2. FATIGUE PROPERTIES OF AUSTRALIAN ESR AND EF STEELS

The general form of the fatigue crack growth properties of steels is shown in Fig. 3. Over a wide range of conditions, crack extension per cycle is controlled by the range of crack tip stress-intensity (ΔK) in an approximately linear manner when represented on logarithmic scales. Over this range, growth rates are insensitive to changes in environment and microstructure, whereas at high ΔK levels, growth rates increase more rapidly, corresponding to the onset of overload fracture mechanisms. Conversely, at low ΔK levels found in components such as axles and shafts which experience many fatigue cycles, growth rates decrease rapidly until crack growth stops at the "threshold" value of ΔK.

A comparison of ESR ordnance steels (of Australian origin) with similar high-quality electric furnace steel indicated that:-

(i)   At high ΔK the improved toughness of the ESR material prolonged the "linear" fatigue region, leading to lower crack growth rates compared with EF steel.

(ii)   At low ΔK, the ESR material showed higher growth rates than the EF steels; further work is in progress to confirm this behaviour, and to determine whether the use of ESR materials could be detrimental to the performance of components designed for long fatigue lives.

Questions

Q: Do you think that ESR could be used in turbine components?

A: Probably not, since these results show that a large number of low stress cycles may lead to failure of ESR steels. The advantages of ESR for gun barrels are that they have practically a zero rejection rate (since there are no large inclusions), and there is a 10% improvement in wear life due to the dispersion of carbides.
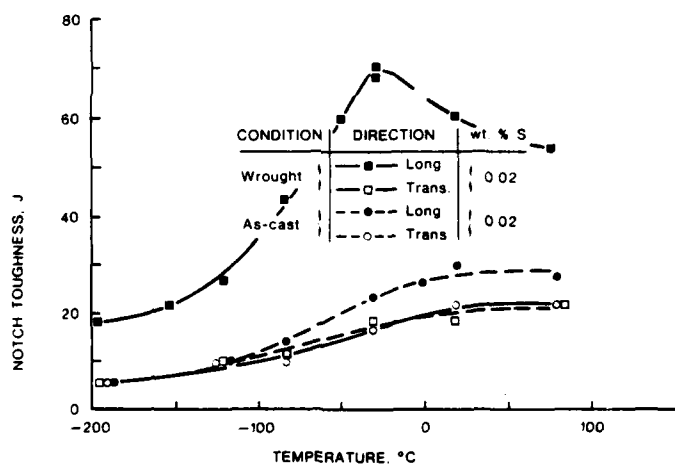
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FIG. 1   Charpy V-notch impact data for as-cast ESR steel and for a wrought
          EF steel.
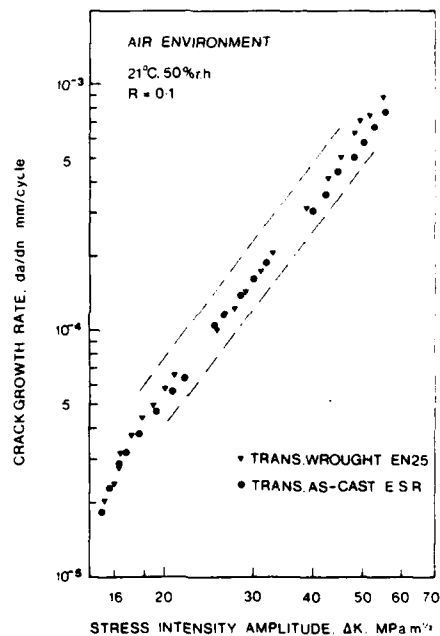
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FIG. 2   Fatigue crack growth properties (increment per cycle as a function
         of stress intensity range) of as-cast ESR and wrought EF steels in
         the T orientation.   The scatter band for L orientation tests on
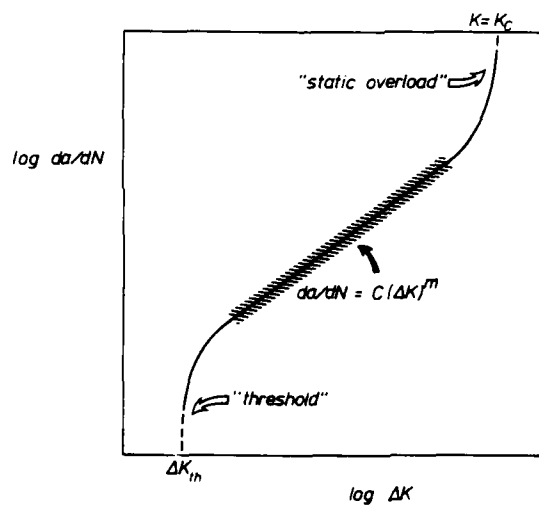   both materials is indicated.

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FIG. 3   Schematic diagram showing form of fatigue crack growth properties of
steels, including an extensive "linear" regime, "overload" region at
high ΔK and "threshold" at low ΔK.

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ELECTROSLAG REFINED STEEL AS AN ARMOUR MATERIAL

Ray Woodward, MRL

Extensive testing of ESR and conventional armour steels in both the USA and the UK has established those conditions for which ESR steels offer considerably improved ballistic properties over conventional armour steels. This work has also highlighted the difficulties of understanding the relation between improved performance and mechanical properties and has shown where manufacturing and testing problems can arise. These aspects of ESR armour steel development are reviewed, with some effort to interpret the data and relate it to the Australian scene.

ESR steels have shown superior ballistic properties to conventional quenched and tempered steels when the hardness exceeds about 40 R_c and these better properties are maximized in the range 50 to 54 R_c. Whether or not ESR steels are better for a particular threat depends on the type of penetrator and the impact conditions, hence it is not always advantageous to go to the ESR steels. Nevertheless it is of value to examine the reasons for the improved performance and to exploit the advantage where it exists.

The range of hardness in which ESR steels show improved ballistic properties correlates with a region where adiabatic shear plugging is observed in conventional steels, and ESR steels appear to be more resistant to this type of failure. Hence the commonly accepted explanation is that ESR steels are more resistant to adiabatic shear through either an increased specific heat or a higher work hardening rate. Since an increased specific heat is unlikely, effort has been concentrated on the work hardening rate which, despite early favourable indications, has given a null result; ESR and conventional steels of the same composition and strength, heat treated the same way, have similar work hardening rates.

ESR steels have greater cleanliness and uniformity of composition and one would therefore expect greater ductility. This does not show up in elongation figures from quenched and tempered plates in the short transverse or rolling directions, although there is a slight indication from reduction of area figures that ESR steels do have better ductility. As elongation reflects the work hardening rate of a material, this supports the earlier statement on the relative work hardening rates of ESR and conventional steels. The reduction in area reflects more the influence of inclusion distribution, hence one can understand the slight indications of improvement in terms of the structure of the ESR steel. In the through thickness direction, however, there is a marked difference in behaviour, ESR steels showing a significant increase in ductility measured in terms of reduction in area. This correlates with the observation in this laboratory by Dr John Yellup that ESR steels show an improved resistance to spalling when subjected to explosive generated shock waves, a test which stresses the through thickness properties of plates.

If it is accepted that the only key difference between ESR and conventional steels is the through thickness ductility, then the only likely explanation of differences in behaviour centres on the influence of inclusions on discing failure. Discing is a fracture occurring during penetration in the plane of the plate, similar to spalling, but not associated with shock wave interactions. The cases of improved performance of ESR steels which have been observed are in a target/projectile relative size range and target hardness range where, for steels, discing failure can be observed alone or to some degree in cooperation with adiabatic shear plugging. Probably the key to the mechanics lies in the interaction between the two modes of failure: discing and adiabatic shear plugging.

Whilst some scientific difficulties remain to be resolved, we turn to exploitation. Small scale experimental work in the US was carried out on a SAE 4340 steel which, whilst having satisfactory ballistic properties, would not meet the normal low temperature toughness requirements of a metallic armour which is also expected to be structurally sound before and after ballistic impact. Unfortunately, scaled up trials continued with the use of the SAE 4340 steel, which showed cracking after some low temperature ballistic tests. This poor structural behaviour was a severe set-back to the program and changes to the steel chemistry were required. This has now been accomplished satisfactorily and a suitable small scale ballistic toughness test developed. This exercise serves as an illustration of the problems which can arise in going from the laboratory to incorporation in an armoured vehicle; in some cases the problems have been solved in the past but forgotten.

Development of ESR steels for armour applications is continuing in both the UK and the USA to exploit its advantages. Australia does not at present have a demonstrated capability to produce quenched and tempered steel plates which meet the structural or ballistic requirements of an armour specification. We do, however, have suitable plant. In view of the planning of Project Waler, it would be timely to establish this capability for both conventional and ESR steels. Such a program would enable ballistic testing to establish clearly the areas in which ESR and high quality electric and/or vacuum steels compete and what the advantages in performance are. It would also allow fabrication trials to be undertaken. Overseas experience in armour applications has demonstrated clearly that the materials technology must be proven in advance if successful incorporation in an engineering design is to be possible.

Questions

Q: Can ESR be used for refining aluminium alloys?
A: It could possibly be used to remove iron, but it is not called ESR. The ESR process has, however, been considered for titanium.

WELDING OF ESR STEELS

Bob Phillips, MRL

1.   INTRODUCTION

       Although many of the present applications of ESR steels do not
involve fabrication by welding, there are certain vital applications where
welding is essential. These include the aerospace field, and repair welding
of defective ESR components. With increased usage of ESR steels envisaged in
the future, it is anticipated that applications involving welding will also
increase. Two likely applications which appear imminent are the welding of
ESR hard steel armour and high yield ESR steel for submarine hulls.

       When welding ESR steels, it would of course be desirable to know
accurately whether they are more or less difficult to weld vis a vis
conventionally melted steels of the same type, and also to know whether we can
expect welded joints in ESR to have improved mechanical properties.

       Unfortunately, the literature specifically referring to the welding
of ESR steels is extremely sparse and that which is available is fragmentary,
and does not clearly answer the above questions. Thus, in order to examine
the welding of ESR steels in a systematic and coherent manner, it is necessary
to extrapolate from the basic principles of the welding of steels of a similar
type, taking into account the special features of ESR steels.

       In examining the welding of ESR steels two main areas will be
covered; namely, potential weld cracking problems and the mechanical
properties of the weldment, particularly weld toughness.   The most
appropriate welding processes which should be used in the fabrication of ESR
steels are also discussed.

2.   WELD CRACKING PROBLEMS

2.1   Heat Affected Zone (HAZ) Liquation Cracking

       This form of cracking can be a significant problem in the welding of
low and medium alloy ultra high strength ferritic steels, austenitic steels,
and inconel super alloys. Cracking is intergranular, confined to the coarse
grained region of the HAZ, and results from the separation of liquid films of
low melting point segregates. The main elements which promote cracking in
ferritic steels are carbon, and the impurities sulphur and phosphorus.

       Looking at the problem of HAZ liquation cracking in ESR steels, it
can confidently be predicted that cracking susceptibility would be greatly
reduced or eliminated for two reasons. These are:

   (i)   The sulphur levels are very low, 0.003 wt% to 0.006 wt%. This
          virtually eliminates the influence of the most deleterious impurity
          element.

(ii)   Some of the calcium present in the slag is partitioned into the MnS
type inclusions in the ESR steel. The nett effect of this calcium
is to make liquation of the inclusions more difficult. Calcium also
probably increases the wetting angles of any liquid segregate,
thereby making grain boundary penetration more difficult.

2.2   Hydrogen-Induced Cold Cracking

In the welding of ESR ferritic steels, as with conventional steels,
hydrogen-induced cold cracking in the weldment is the most serious type of
defect likely to be encountered. The main factors which promote cold cracking
under normal welding conditions are the presence of a susceptible
microstructure and a sufficient concentration of hydrogen. In practical
terms, the risk of cracking in both the weld metal and the HAZ increases with
increasing hardness of the susceptible microstructure.

To date, no direct data has been published regarding the relative
susceptibilities of ESR and conventionally melted steel to weldment cold
cracking. Not withstanding the lack of direct evidence, it has been
established by several investigators that, for ferritic steels, decreasing the
sulphur level to say 0.005%, causes an increase in the risk of cold
cracking. Most of these studies relate to C-Mn and microalloyed steels where
it has been established there are two separate effects, namely:

(i)   the hardenability is increased by reducing the sulphur level

(ii)   the susceptibility of the matrix is increased because there are
fewer inclusions to act as hydrogen sinks.

Transposing this information back to ESR steels, it is still unclear
whether we would expect them to be more susceptible to cold cracking. To be
more explicit, hardenability usually does not enter into consideration in high
strength steel weldments and any detrimental influence of a lower volume
fraction of sulphide type inclusions in ESR steel may well be counterbalanced
by the homogeneous matrix and uniform dispersion of inclusions. It can safely
be concluded that any detrimental effect due to low sulphur levels is likely
to be quite secondary to that of microstructural hardness and hydrogen
concentration.

2.3   Lamellar Tearing

Certain types of joint such as T butt welds, corner welds and T
fillet welds experience severe welding stresses in the through thickness
direction of at least one of the joint components. If ductility in the short
transverse direction is low, cracking may result especially in thicker
sections (> 25 mm) in the HAZ. These lamellar tears, as they are called, are
almost invariably associated with planar inclusions, e.g. sulphides and
silicates lying parallel to the plate surface.

As one of the hallmarks of ESR steels is their excellent ductility
in the short transverse direction, it can confidently be predicted that they
would be virtually immune to lamellar tearing problems.

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2.4 Weld Metal Solidification Cracking

In an analoguous manner to HAZ liquation cracking, this form of cracking results from the rupture of low melting point segregate films between solid dendrites. The main elements which promote cracking in ferritic weld metals are again carbon, and the impurities sulphur and phosphorus.

Clearly there is potential for a reduction in the problem when welding ESR steels, but the extent to which the problem can be reduced will depend on the degree of parent plate dilution. In a high dilution situation where all the weld metal comes from the parent plate, such as in electron beam welding, a reduction of sulphur in the parent material is highly beneficial. Conversly, in a low dilution situation, such as occurs in the welding of thick sections using manual metal-arc, most of the impurity contribution comes from the filler wire, and the cleanliness of the steel is of far less significance.

3.　WELD METAL TOUGHNESS

In the welding of ferritic steel, it is generally found that as the strength of the deposited weld metal increases, its toughness decreases. This can become a very serious problem in the welding of ultra high strength steels where the toughness of the weld metal is usually lower than any other region. The factors influencing weld metal toughness are quite complex and their interrelationship is still not fully understood.

One factor of special relevance to ESR steels is the detrimental influence of non metallic inclusions, particularly sulphides and oxides, on fracture initiation and propagation. Thus in the welding of ESR steels we would expect improved toughness, particularly in a high dilution situation. This improvement would probably be attenuated as the dilution by the parent material decreased, unless the added filler wire was extremely clean.

4.　WELDING PROCESS

The choice of the most appropriate welding process is of greatest importance in the welding of high strength ESR steels, where one is aiming at a joint performance which matches that of the parent. Although many welding process are available, only 5 or 6 would be commonly considered for high quality welding of ESR steel; these are manual-metal arc (MMA), metal inert -gas (MIG), submerged arc (SA), tungsten inert-gas (TIG), Electron beam (EB) and laser welding. Even these processes are not equally suitable and each has special areas of application depending on weld quality, productivity etc. For instance:

(A)　MMA is considered suitable for matching strength welds with yield strengths up to 1000 MPa, but difficulties are experienced as the 1000 MPa level is approached. The main problems are cold cracking and weld toughness. It should be remembered that MMA is a

relatively low dilution process which tends to give moderate sulphur and oxygen levels in the weld metal.

(B)   For steels with yield strengths between 700 MPa and 1000 MPa, MIG is considered to be a more suitable mechanised process than SA because it gives better toughness.

(C)   For weld metals above 1000 MPa yield TIG or EB should be used for optimum weldment toughness and minimium risk of cold cracking. In this respect, electron beam welding would generally be preferred where available because:

(i)   it allows autogenous welding in thick sections

(ii)   it results in low distortion due to the narrow weldment

(iii)   it results in a very clean weld because there is no possibility of atmospheric contamination.

5.   CONCLUDING REMARKS

Basically, the difficulty of welding high strength ferritic steels is more related to the carbon level of the steel, its bulk chemical composition and the strength level required, than it is to the particular steel making process used to produce the steel. It is, therefore, likely that overall the differences in the weldability of ESR and conventionally produced steels are relatively minor. To some extent this may explain the paucity of literature specifically relating to the weldability of ESR steels.

None-the-less there are certain potential differences in weldability which should be highlighted. For instance, we would expect ESR steels to possess superior weldability in respect of their resistance to HAZ liquation cracking, lamellar tearing and weld metal solidification cracking than their air melted counter-parts, primarily because of the low sulphur levels and the fine dispersion of sulphides. Furthermore, we would expect ESR steels to have the potential to produce tougher weldments in high dilution situations because of lower levels of sulphides and oxides.

In the case of cold cracking, the picture is uncertain although these is a suspicion that ESR steels may be more susceptible. If this were the case we would expect the effect would be small and only of minor importance.

Questions

Q: Concerning hydrogen-induced cracking in weldments, would it be beneficial to remove hydrogen from the steel by vacuum during the steel-making process?

A: Not really, because the great bulk of hydrogen associated with weldment does not come from the steel itself, but arrives in the weld metal from breakdown of water vapour and grease during the welding process.

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MACHINING OF ESR STEELS

Derry Doyle, MRL

In the machining literature, there is a dearth of information concerning the machinability of ESR steels. User reaction is varied, some claim 'poor' machinability while others claim that they experience no problems or even some improvements. In the absence then of any clear definitive study, the picture is somewhat confused.

There is no doubt that this is a result, in part, of the ill-defined and non-quantifiable nature of what is meant by machinability. The term covers a multitude of machining processes which in turn cover a range of variables such as feeds, speeds and depth of cut. Not withstanding all these problems, there can be little doubt that the expectation regarding the machinability of ESR steels would be that they would have 'poor' machinability. This is based on the well appreciated fact that enhanced machinability can be brought about by re-sulphurising steels (that is, by increasing the sulphur content). This begs the question of just what is the role in chip formation of a minor phase addition such as sulphur? Although some considerable effort has gone into attempting to answer this question, there is as yet no clear consensus.

Basically, minor phase additives which are beneficial for machining are thought to influence both the dynamic shear stress on the shear plane (area 1 in Fig. 1) and the friction conditions at the chip/tool interface (area 2 in Fig. 1).
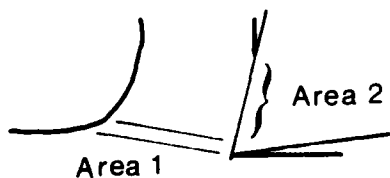

Fig. 1

Fig. 2

In area 1 in Fig. 1, it has been postulated that the minor phase additives initiate microcracks which in turn reduce the area capable of withstanding the applied shear stress. However, calculations of the dynamic shear stress based on measurements of cutting forces indicate that the minor phase additions have little or no influence. In area 2 in Fig. 1, it has been postulated that the deposition of sulphur as a low shear strength film on the rake face of the cutting tool acts to reduce the frictional resistance to sliding of the chip against the tool.

The hypothesis that the beneficial effect of sulphur on machinability is primarily to reduce friction was further investigated at MRL. In a series of experiments, samples of commercial grade En25 steel and ESR equivalent grades were machined inside a scanning electron microscope. Typical compositions of the two grades of steels are shown in Table 1.

T A B L E 1

	C	S	P	Si	Mn	Ni	Cr	Mo	O
ESR	0.34	0.005	0.011	0.32	0.67	2.28	1.07	0.66	0.002
En25	0.30	0.010	0.018	0.46	0.66	2.10	0.66	0.60	0.008

The advantage of a machining study of this kind is that the chip forming process, although done very slowly at 2 mm/min, can be observed in situ and at very high magnification.   These experiments showed that with the ESR grades a continuous chip (of the form shown in Fig. 1) formed initially, but very quickly degenerated into a continuous chip plus built-up edge (bue) (of the form shown in Fig. 2).   The latter chip type forms as a direct consequence of high friction on the rake face of the cutting tool.   The commercial grade En25, however, machined for very much longer periods before the transition from continuous formation to one with a bue occurred.   This indicates a general principle that the frictional interactions which arise when machining ESR steels will be more severe than when machining equivalent commercial grades.

It further follows from this that the higher friction will mean higher temperatures at reasonable cutting speeds, which must lead to a degradation in tool life.   This degradation should not seriously embarrass users, since there is a vast range of modern cutting tools now available on the market capable of withstanding the high temperatures generated when machining ESR steels.   In addition, it is frequently reported that higher temperatures in machining lead to lower cutting forces and improvements in surface finish.   This may well explain why some users have claimed superior machinability based on surface finish criteria, with tool life being of only secondary consideration.

In conclusion, it is axiomatic, it seems, that demands for improved steel quality may necessitate a compromise between suitability for machining and in-service performance characteristics.

CORROSION OF ELECTROSLAG REFINED HIGH STRENGTH STEELS

Roger O'Halloran, Russell Taylor and George Weston, MRL

Electroslag refining is an attractive production route from the corrosion viewpoint in that it offers cleaner steels coupled with smaller inclusion sizes and a more homogeneous solidification structure.

Corrosion in high strength steels spans general and localised attack, hydrogen-related failure, environmental cracking under stress, and corrosion fatigue. The literature is very sparse in the area of ESR high strength steels. In a comparison of the corrosion of three constructional steels refined by electron beam, vacuum arc and electroslag techniques, ESR materials corroded fastest in acid but were found to be superior in fatigue tests. The poor performance in acid was attributed to alumina inclusions. All three refining techniques led to improvements over the parent material (1). Comparisons of air-melted stainless steel prior to and after ESR showed a lowering in corrosion rate of up to 50% and smaller variations in corrosion according to position in the ingot (2). Finally, the stress-corrosion resistance of electric furnace HY-130 steel in 3.5% NaCl has been shown to be higher after ESR and attributed to the more homogeneous structure of the refined material (3).

Experimental work has been performed at MRL on transverse surfaces of a number of electric furnace and ESR samples of AISI 4340 and En25 steels with sulphur contents ranging from 0.002-0.025 wt.%. Corrosion of rotating discs of all steels in aerated 3.5% NaCl was uniform over the surfaces and independent of sulphur content since the rate is determined by the rate of supply of oxygen and not the surface structure.

Electrochemical tests for pitting were performed in 3.5% NaCl in the absence of oxygen. In contrast to the work of Semino and Galvele (4), polarisation curves were extremely non-reproducible and the only material which showed a pitting tendency was an electric furnace steel with the highest sulphur content (0.011%).

ESR specimens were examined in dilute, aerated NaCl solution using a scanning reference electrode under computer control (5) which produces a corrosion map of a surface. Corrosion occurred at discrete sites which, over a 24 hour period, were more numerous and more mobile for samples with high sulphur content. The sites were more mobile for surfaces polished with Al_2O_3 than when diamond paste was used.

Finally, the range of steels was subjected to ASTM test method G48-76 (1980) for pitting in alloy steels. All samples underwent pitting corrosion, the deepest pits being observed for steels with high sulphur content, regardless of ESR. However, the average maximum pit depth of En25 steel with 0.011% sulphur was eight times greater for electric furnace steel than that for ESR steel with the same sulphur content.

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In conclusion, the literature together with the experiments described above indicate that corrosion resistance is at least maintained and generally enhanced by the electroslag refining process.

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SUMMARY OF GENERAL DISCUSSION

1. The uniformity of steels from the ESR process needs to be stressed, we can QA the ingot, and only get carbon at the bottom. There is excellent consistency within an ingot.

2. The OFM concern regarding increased forging costs with ESR steels was considered unfounded as evidence suggests that maximum mechanical properties are obtained with ESR steels at lower forging reductions than with conventional steels. In addition, the lower forging temperatures suggested by OFM were considered unnecessary on the grounds that the influence of grain boundary sulphide precipitation (overheating) at temperatures up to 1250°C has been found to be small, while any hot working on a falling temperature would break up any grain boundary sulphide networks that had been formed. Therefore, little disadvantage is seen in using a similar forging temperature for both ESR and conventional ingots.

3. For the manufacture of medium calibre gun barrels, ESR steels have not been adopted due to their high cost, even though some batches of ESR steels examined have had very high quality. The stop-start nature of Australian defence manufactures lends itself to the use of ESR steel.

4. We have no results on the autofrettage of ESR gun barrels, but we would expect that autofrettage produces a uniform level of residual stress.

5. The cost of ESR steel has been reduced by Comsteel, with a premium of 10%-50% per ingot tonne being charged.

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