International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-5 Issue-3, February 2016

Improvement in Mechanical Properties of Ultra High Strength Steel through Induction Melting and Electroslag Refining

A. K. Rajak, S. K. Maity, Nagendra Prasad

Abstract- ***The objective of the present study is to develop the ultrahigh strength steel by induction melting and electroslag refining, which is followed by thermomechanical treatment with yield strength in excess of 1600 MPa and elongation of 9-10% . Ultrahigh strength steels are used in fabrication of rocket motor casings, aircraft undercarriages, turbine motors, pressure vessels and offshore platforms. Some of the currently employed imported steels, like maraging steel is highly alloyed and is expensive . In the first part, the alloys were prepared by induction melting with addition of calculated amount of scrap and ferroalloys. The molten metal was tapped at 1600⁰C and poured in preheated cast iron mould of 48x52x250 mm in dimension. The other alloy is prepared by addition of 0.024% Ti to the base composition. This alloy exhibits better mechanical properties than previous one. In the second part of investigation, Attempts were made to develop steel containing low sulphur and low phosphorous through electroslag refining (ESR) process followed by thermomechanical treatment (TMT). The other alloy was prepared by inoculation of about 0.058% titanium during ESR process. Alloys developed by ESR process resulted in sound ingot with low inclusions. The ESR ingots were further undergone for thermomechanical treatment (TMT) to convert it into plates. The process consist of pre-rolling of the ESR ingot to a bar at 1200℃, followed by hot rolling in two passes starting from 950℃ and finishing at 850℃ with equal deformation of 25% in each pass to convert the bar into plates and were immediately cooled in oil. The mechanical properties and some microstructural features were characterized with the specimens prepared from plates. The base alloy displayed UTS of 1792 MPa, yield strength of about 1580 MPa and elongation of 7.6%. Titanium inoculated alloy displayed UTS of 1885 MPa, yield strength of 1700 MPa and elongation of 8.3 %. It can be construed that the mechanical properties of the titanium inoculated alloy were substantially improved compared to base alloy. Optical and SEM microstructures of the TMT specimen's reveals predominantly lath martensites. However, the microstructure of titanium inoculated alloy consisted of small packets of finer lath martensite. Titanium addition reduces the grain size and refines the martensite laths that lead to improvement in mechanical properties.***

Keywords: Ultrahigh strength steel, Electroslag refining, Themomechanical treatment, Microstructure, Mechanical properties

Manuscript published on 28 February 2016.
* Correspondence Author (s)
A. K. Rajak, Department of Metallurgical Engineering, Birsa Institute of Technology, Sindri, Dhanbad, India.
S. K. Maity, CSIR- National Metallurgical Laboratory, Jamshedpur, India.
Nagendra Prasad, Department of Metallurgical Engineering, Birla Institute of Technology Sindri, Dhanbad, India.

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an open access article under the CC-BY-NC-ND license http://creativecommons.org/licenses/by-nc-nd/4.0/

I. INTRODUCTION

Structural steels with minimum yield strength of 1380 MPa are often classified as ultrahigh strength steel (UHSS)[1] . These are used in many critical applications like in the fabrication of rocket motor casings, aircraft under-carriages, turbine motors and pressure vessels, etc. In addition to high strength-to-weight ratio, these steels should have good ductility, toughness, fatigue resistance and weldability. Some of the currently employed steels, like maraging steels, are highly alloyed and expensive. Search for less expensive steels with better properties, is therefore a continuing process is therefore one of the objective of this study.
High strength of these alloys is obtained by employing different strengthening mechanisms like
i) grain refinements ii) precipitation hardening iii) thermomechanical treatment iv) martensite transformation [2-4] by careful control of alloying and subsequent processing. Many defects are normally introduced, and inferior properties are obtained, during induction melting and solidification process. Electroslag refining (ESR) process is often employed to obtain superior properties than induction melting in these materials for critical applications. Alloys developed by ESR process normally resulted in sound ingot high strength, fracture toughness and improved weldability with low inclusion. Therefore this process was adopted as the standard production method for the alloys [5]. ESR reduces sulfide and oxide inclusions. Application of this refining technique has resulted in minimizing directionality in properties and improvements in fracture toughness at ultrahigh strength levels.

It is well known that the thermomechanical treatment in high strength steels results in higher strength properties without reducing ductility or brittle fracture resistance[6]. Thermomechanical treatment (TMT) involves controlled plastic deformation and phase transformation [6]. It is possible to obtain considerable refining of the microstructure directly after finish rolling or by using additional accelerated cooling. It is also reported that if rolling is completed at a relatively high temperature (in the high temperature austenite range) and the alloy is cooled in air, one gets a mixed microstructure of upper bainite and martensite. Accelerated cooling results in the formation of martensite with less bainite [7].

One of the primary aims of the proposed work is to develop an alloy with ultra high yield strength with adequate ductility and toughness.

As attempts has been made to enhance the mechanical properties with better ductility The strength and toughness was achieved through following process techniques.

- Adjustment of chemical composition and inoculation of Ti,
- Precipitation of carbonitrides of Ti, V, Mo and Cr ,
- Processing through ESR,
- Processing through control thermomechanical treatment.

II. METHODOLOGY

2.1. Induction melting and thermomechanical treatment

First of all some heats were conducted through induction melting. This study was useful to optimize the process parameters to achieve the required composition through air induction melting. The scrap and ferroalloys are added in a calculated amount to achieve the desired chemical composition. After large number of trials and optimization of the process conditions, two alloys (base and Ti-inoculated) are prepared in 20kg open air induction furnace. The molten steels were tapped at 1600^0C and poured into preheated cast iron mould of dimension 48×52×250 mm. After solidification, the cooled ingots were taken out from the mould, and were homogenized in a muffle furnace at 975°C for 8-9 hours. About 20 mm lengths were cut from the bottom and top of the ingot. The ingots were approximately 220 mm long. About a length of 100 mm were taken from the ingots to investigate the properties in as-cast condition. The specimens were austenitized at 975°C followed by oil quenching. Then specimens were tempered at 475°C. The remaining part of the ingot was undergone for thermomechanical treatment. This treatment was carried out in a selected schedule of soaking, rolling and cooling. The ingots were soaked at 1100°C for about one hour and were forged into 17 mm plate. During final rolling, the bars were re-heated at 1100°C. It was transported to rolling mill and as soon as the temperature was dropped to 950°C. After that it was allowed to roll for first pass. The plates were allowed for second pass (final pass) at 850°C. Thereafter, immediately the samples were quenched in the oil. The final thickness of the plate was approximately 12 mm. The samples were prepared for mechanical properties and microstructural studies.

2.2 ELECTROSLAG REMELTING (ESR)

Over the last few decades electroslag remelting (ESR) process was used to produce high quality steels of different size of the ingot [8]. The process consists of remelting of the metal to be refined in the form of a consumable electrode through a molten slag pool. The remelting is initiated when the end of the electrode is brought into contact with the molten slag bath. The slag is contained in a stationary mould, or a mould that can be raised as the ingot solidifies. As the temperature of the slag bath rises above the melting point of the metal droplets comes out from the tip of the electrode. Since the molten steel has a higher density than the slag, droplets pass through the slag and are collected at the bottom of the mould as a liquid which quickly solidifies, leading to progressive build up of an ingot. During the passage of the metal droplet through the molten slag, a chemical reaction occurs with slag. Due to the large metal-slag interfacial area non-metallic inclusions are removed. A schematic representation of the ESR process is shown in Figure 1.

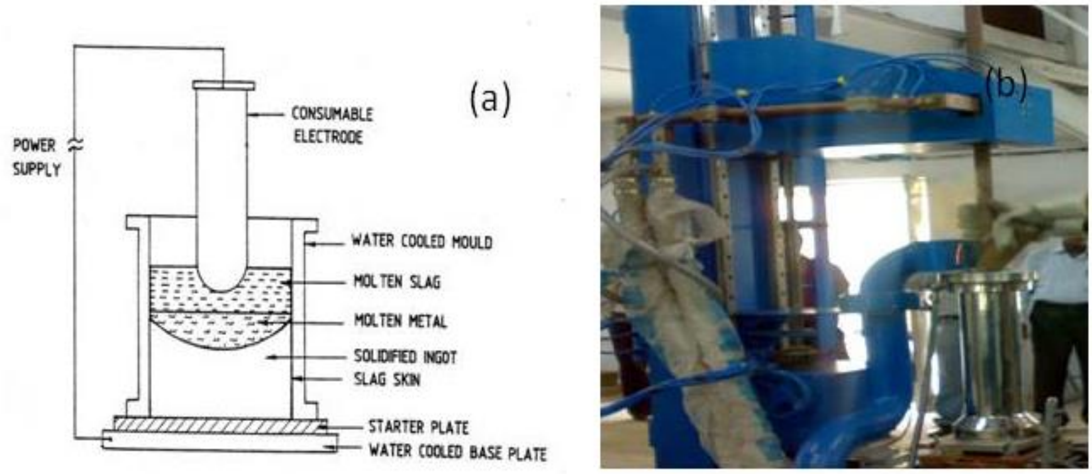


Figure 1: Schematic illustration of an ESR-unit (a) and ESR set up at NML JSR (b)

2.2.1 PREPARATION OF SLAG

Acid grade fluorspar (96% CaF_2) and Bayer alumina (99% Al_2O_3) in 70:30 (wt %) were mixed thoroughly. The liquidus temperature of the flux of this composition is about 1250°C. The mixture was fused at about 1600°C in an air induction furnace in a 15 kg graphite crucible. The melt was held at 1600°C for 20-25 minutes till foaming stopped, and was poured into a pre-heated graphite crucible and was allowed to solidify. The solidified mass was crushed and screened to get granular particles (-20 mesh) and it was stored.

2.2.2 PREPARATION OF ELECTRODE AND INGOTS

The electrodes for ESR were prepared in a 20 kg air induction furnace with calculated amounts of scrap and ferroalloys. Following was the sequence of addition of alloying elements:

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

FeSi (75 % of total) → FeMo → low carbon FeCr → high carbon FeCr

FeSi (25 % of total) → FeMn → Ni → FeV → 0.1 % Al (added in ladle)

The tapping temperature was about 1650°C and the metal was cast into 40 mm diameter and 600 mm high vertical chill moulds. The photographs of the electrodes are shown in Figure 2(a). These were remelted through ESR process with and without inoculation of 0.05-0.07% Ti. The alloys were prepared through induction melting followed by electroslag refining (ESR) as shown in Figure 2(b). The process was carried out in a water cooled steel mould of 80 mm diameter connected to negative end of DC power source. The applied current & voltage were about 730 amps, and 25 ± 2V respectively, with mould water flow rate of 30 liters /minute and base-plate water flow of 20 liters /minute. In one of the heat, the melt was inoculated by titanium through a steel tube of 8mm OD X 6mm ID filled with calculated amount of Fe-Ti. After ESR, cooled ingots were taken out from the mould and homogenized in a muffle furnace at 975°C for 8-9 hours. About 20 mm and 10 mm lengths were cut from the bottom and top of the ingots respectively. Each ESR ingots were approximately 150 mm long and 6 kg in weight. The ESR ingots underwent for forging and thermomechanical treatment (TMT).

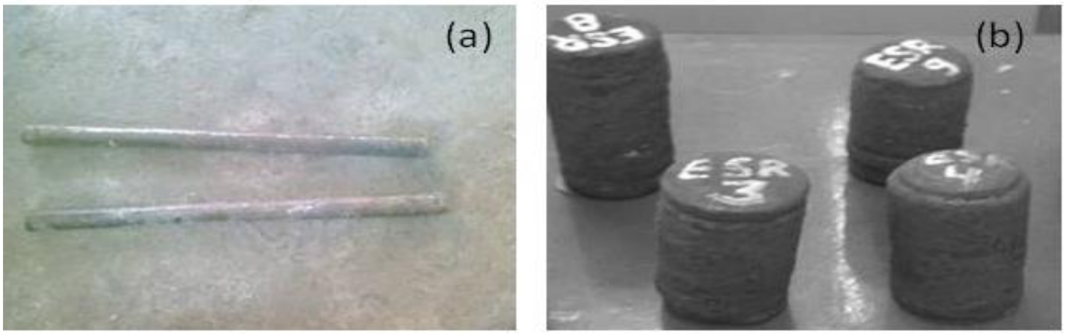


Figure 2: ESR electrodes ready for remelting and refining

2.2.3 THERMOMECHANICAL TREATMENT (TMT) OF INGOTS

The ESR ingots were soaked at 1100°C for about one hour and were forged and pre-rolled into 25 mm x 50 mm bars. During final rolling, the bars were re-heated at 1100°C, soaked for 90 minutes. It was rolled to about plate of size 12 mm x 70 mm and finished at 850°C. Thereafter, immediately the samples were quenched in oil. About 10 mm and 2 mm lengths were cut from the both ends and the sides of the plate, respectively.

III. CHARACTERIZATION

Chemical analysis was carried out by atomic absorption spectroscopy (AAS). For optical and SEM studies the specimens were mounted and polished by conventional methods. Mechanical properties were evaluated as-TMT condition. For tensile test, round specimens of 4 mm diameter and 24 mm gauge length were prepared, as per IS: 1608, 1972, and tested at room temperature using the Servo Hydraulic UTM. Charpy V-notch impact toughness specimens were prepared as per IS: 1499, 1977. Hardness was measured on Rockwell C hardness tester. ½ CT fracture toughness sample were prepared to evaluate the fracture toughness values. Optical, SEM samples were prepared as per standard procedures and fractrographs were collected from the broken impact specimens.

IV. RESULTS AND DISCUSSIONS

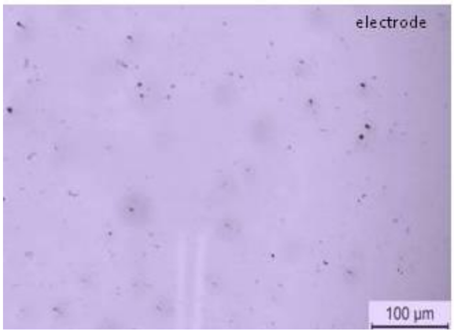
The chemical composition of the base alloy and the Ti-inoculated alloy prepared through induction and ESR are shown in Table 1. It can be seen that the chemistry of IND-1, IND-2,ESR1 and ESR 2 are similar except 0.028% and 0.58% titanium was added in IND-2 and ESR 2 alloy. These alloys were prepared in open air induction furnace. Due to this the amount of Titanium cannot be obtained in the required level (i.e. ~0.06%). Other alloying elements were maintained in the anticipated values. In ESR ingot Ti obtained in the required level 0.58%. ESR ingots were prepared with electrodes prepared by induction melting. Photograph of the ESR ingots are already shown in Figure 2. It was observed that ingots had smooth and bright surface with few blemishes on the surface.

The loss of alloying elements was typically 5% from induction melt to ESR. ESR slag have large sulphide capacity, and the large liquid metal/slag interface area which ensures high rates of sulphur transfer to slag. The sulphur and phosphorous content in all ESR ingots has been substantially reduced compared with the corresponding induction melt electrodes. Inclusions in the samples before (electrode) and after (ingot) ESR processes are shown in Figure 3. It can be observed that sulphur and phosphorous in electrodes was about 0.026% and 0.28%, respectively. In ESR alloys, sulphur and phosphorous was about 0.011%,0.012% and 0.015, 0.017 %, in ESR1 and ESR2 respectively. It can further be reduced depending upon the quality of prefused slag.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

Table 1: Chemical composition of Induction and ESR ingots

Alloy	C	Mn	Si	Cr	V	Mo	Ti	S	p	N	Remarks
Ind-1	0.22	1.13	0.15	5.54	0.426	1.01	NA	0.026	0.032	0.18	Base alloy
Ind-2	0.23	1.17	0.13	5.59	0.343	1.008	0.028	0.028	0.032	0.17	Ti- alloy
ESR 1	0.23	1.05	0.17	5.7	0.40	1.18	NDA	0.011	0.015	0.02	Base alloy
ESR 2	0.21	1.12	0.14	5.49	0.324	1.05	0.58	0.012	0.017	0.03	Ti- alloy



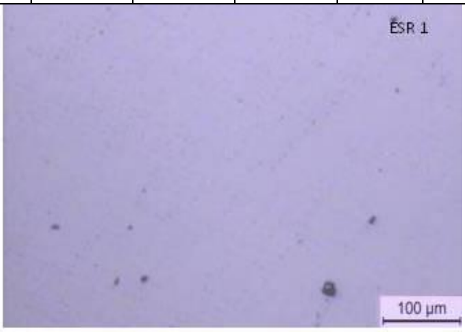


Figure 3: Inclusion in base alloy before and after ESR process of ESR1

4.1 MECHANICAL PROPERTIES OF TMT PLATES OF ELECTRODE AND INGOTS

The tensile strengths, yield strengths and elongations of the hot rolled samples in the oil cooling condition (TMT) are shown in Table 2. It can be noticed that the tensile properties of ESR 1 ingot is better than induction alloy (IND 1). When Ti is inoculated with the composition of base alloy, namely in IND 1 and ESR2 steel, the strength values was substantially improved (UTS: 1848 MPa, Y.S: 1580 MPa, UTS: 1880 MPa, Y.S: 1705 MPa, %El: 8.4 respectively). The room temperature impact toughness values (V-notch) of the rolled samples are shown in Table 2. It can be seen that the tensile properties and impact toughness and hardness values are improved in induction 2 and ESR2 alloy by inoculation of titanium. It can also noticed that charpy impact and hardness value are improved in ESR ingot than induction melt.

Table 2: Mechanical properties TMT plates of Induction melt and ESR alloys

Alloy	Tensile Properties			Charpy Impact (J)	Hardness (Rc)
	UTS (MPa)	Y.S (MPa)	Elongation (%)		
Ind-1	1750	1455	NA	9.1	47
Ind-2	1848	1580	NA	10.1	51.3
ESR1	1795	1585	7.6	15	50.12
ESR2	1880	1705	8.3	28.5	52.35

4.2 MICROSTRUCTURE OF TMT PLATES OF ELECTRODE AND INGOTS

Optical microstructures of the TMT specimens are shown in Figure 4 and the corresponding SEM microstructures in Figure 5. The figures show that the microstructures of the both alloys seem to be consisting of lath martensites. It can be noticed from the micrographs that ESR ingots have better and finer structure than induction melted alloy. One can however see some changes in the microstructure in titanium inoculated alloys. It seems that the laths are more finer in Ti-added alloys compare to the base alloy. The structure of ESR2 alloy consists of small packets of finer lath martensite.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

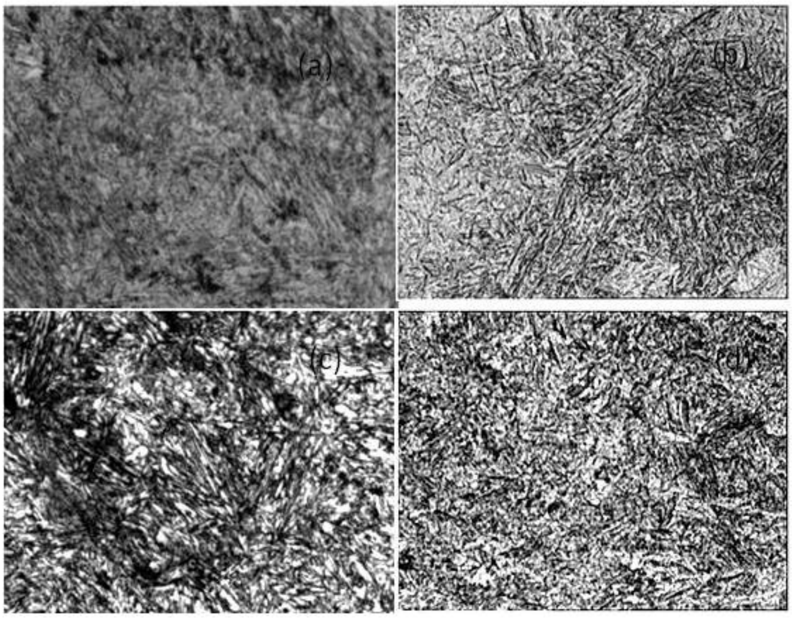


Figure 4-: Optical micrographs of TMT plates of induction alloys (a) (b) and ESR alloys (c) (d)

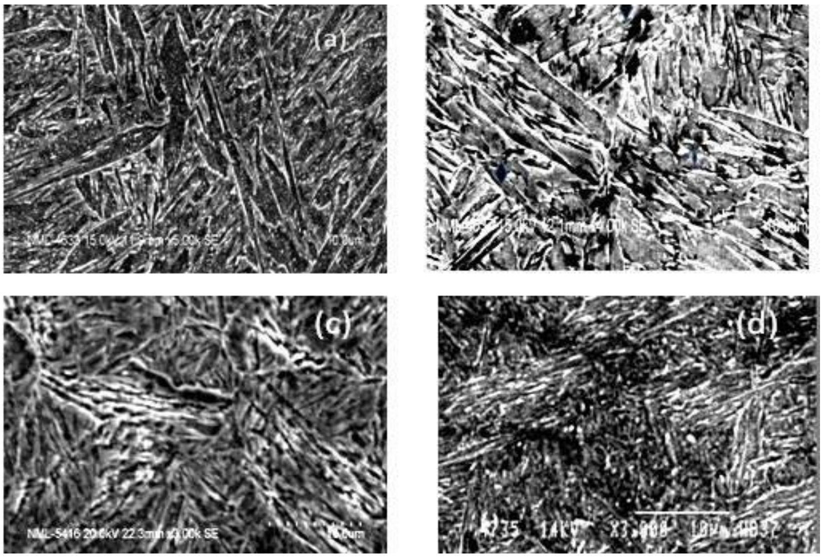


Figure 5: SEM micrographs of TMT plates of induction alloys (a) (b) and ESR alloys (c) (d)

V. CONCLUSION

- Alloy developed by ESR process results low inclusions and better mechanical properties.
- Among the alloys prepared by induction melting, and ESR the Ti added alloys displayed improved mechanical properties compare to the base alloy.
- Ti addition reduces the grain size and refines the marten site laths in IND-2 and ESR2 alloys.
- Both the alloys consist of predominantly lath martensite microstructure.
- The base alloy, ESR1, used for comparison with ESR2, shows predominantly lath martensite structure. The alloy has UTS of 1795 MPa, yield strength of about 1585 MPa, elongation of 7.6%. This is an ultra high strength steel (UHSS).
- Inoculation of titanium in base alloy (namely ESR2) results UTS of 1880 MPa, yield strength of ~1705 MPa, elongation of 8.3 %.
- Titanium inoculation results improvement in mechanical properties possibly by refinement of laths in martensites, reduction of grain sizes and precipitation hardening.

ACKNOWLEDGEMENT

The authors wish to express their sincere thanks to Director BIT Sindri, Dhanbad, Jharkhand and Director, CSIR-National Metallurgical Laboratory, Jamshedpur.

REFERENCES

1. T. V. Philip and T. J. McCaffy, Ultrahigh Strength Steel in Metals Handbook, 10th Ed., ASM International, USA, 1990, pp. 431-435.
2. Bee, J. V., Howell, P. R. and Honeycombe, R. W. K., Metal.Trans., Vol. 10, 1979, .1207.
3. Mazanec, K., Neue Hütte, Vol. 31, 1986, p.21.
4. Hyspecka, L. and Mazanec, K., Iron and Steel Institute, Vol. 1,1973, p.375.
5. J. Pacyna, Steel Research, 57 (1986) 586.
6. K. Mazanec and E. Mazancova, Physical Metallurgy of Thermomechanical Treatment of Structural Steels, Mbridge International Science Publishing, London, 1997.

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)
© Copyright: All rights reserved.

7. C. Ouchi, Multipurpose Accelerated Cooling System, Kawasaki Steel Corporation, Report, 1985.
8. W. E. Ducworth, G. Hoyle, "Electro-Slag Refining", British Iron and Steel Research Association, London, 1969, pp.1-50.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)
© Copyright: All rights reserved.