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Study of the fracture surface morphology of impact and tensile tested cast and forged (C&F) Grade 91 steel at room temperature for different heat treatment regimes

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ABSTRACT

Cr-Mo creep strength enhanced ferritic (CSEF) steels are mainly used in nuclear reactors and ultra-supercritical (USC) power plants for superheater tubes and header. The present research deals with the analysis of fracture surface of the tensile and impact tested specimen of cast and forged (C&F) modified 9Cr-1Mo (P91) steels, which are subjected to different heat treatment regimes. The heat treatment temperatures were 350 °C, 650 °C, 760 °C and 1000 °C, respectively. The heat treatment was carried out a particular temperature for 2 h duration. The fracture surface of tensile and impact tested specimen were also studied for a varying time duration from 2 h to 8 h for a fixed tempering temperature of 760 °C. The heat treatment effect on tensile properties, toughness, Vickers hardness and particle size was also studied. Heat treatment has a noticeable effect on mechanical properties of C&F Grade 91 (X10CrMoVNNB9-1) steel. Fracture morphology is strongly affected by the microstructure and presence of secondary phase particles. The fracture surface was analyzed by using the field-emission scanning electron microscope (FE-SEM). The fractured tensile sample mainly indicates the presence of transgranular ductile dimples and transgranular cleavage facets for heat treatment temperatures of 350 °C, 1000 °C and 1040 °C. The percentage of cleavage facets on the tensile fracture surface was found to decrease for sample heat treated at 760 °C. Less amount of ductile dimples was noticed on the fracture surface for the samples heat treated at 650 °C and 760 °C (furnace-cooled). The so-called 'splitting' fracture was noticed for the sample heated at 760 °C. The 'splitting' fracture becomes more pronounced with the increase in tempering duration from 2 h to 8 h. The sample heat treated for 1000 °C, mainly indicates the cleavage facets on the fracture surface. The fracture mode of impact tested specimen is more complex and shows both ductile dimple tearing and quasi-cleavage facets for heat treatment temperature of 650 °C, 760 °C and as-received condition. The impact failure zone of sample heat treated at 350 °C and 1000 °C indicates the presence of so-called 'river pattern' on the fracture surface.

1. Introduction

The high-temperature CSEF steels are mainly developed for the ultra super-critical (USC) thermal power plants and nuclear plants [1]. The requirement of CSEF steels mainly related to the environment protection from the limitation of the emission of the greenhouse gases such as CO_2 into the atmosphere [2]. To limit the CO_2 emission into the atmosphere, number of projects,

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Table 1
Chemical composition of as-received cast and forged Grade 91 steel, wt.%.

Element	Chemical composition, wt.%												
	C	Mn	W	S	Si	Cr	Mo	V	N	Ni	Cu	Nb	Ti
P91 steel	0.1	0.5	<0.01	0.01	0.3	8.5	0.9	0.1	<0.02	0.4	0.06	<0.01	0.01

new grade ferritic and martensitic steels, cast rolled (C&R) and cast forged (C&F)steels have been introduced in nuclear and thermal power plants. Grade 91 (X10CrMoVNNB9-1) steel is one of the most promising steel used in USC and nuclear power plants. In the 1970s, the Oak Ridge National Laboratory (ORNL) developed Grade 91 steel as modified 9Cr-1Mo steel [3]. The modification of 9Cr-1Mo steel included the addition of strong carbide and nitride forming element such as V and Nb along with small amount of N to enhance the high-temperature creep strength for the long duration [4]. Grade 91 (X10CrMoVNNB9-1) steel also offers the good weldability, high thermal expansion coefficient, high corrosion resistance, good toughness, high thermal conductivity and good ductility at high temperature (650 °C) [4–6]. The Grade 91 steels are mainly used for piping and tubing in nuclear and thermal power plants. Grade 91 steel is generally used for high-temperature application up to 650 °C. At such high-temperature material undergoes the microstructural change such as grain coarsening, thermal straining of particles and precipitation of new phases which may lead the degradation of mechanical properties [7]. The main phases which are observed in P91 steel are $M_{23}C_6$ (M: Cr, Fe, Mn and Mo), MX (M: V, Nb; X: C, N), M_7C_3 (M: Fe, Mn and Cr), M_3C (M: Fe) and M_2X (M: Fe and Cr) [8,9]. The presence of secondary phase precipitates in Grade 91 steel acts as void during the service condition [10,11]. The cracking of secondary phase particles and decohesion of precipitates at the particle/matrix interface might affect the fracture morphology of the surface of Grade 91 steel during room temperature mechanical testing. The microstructure of steel also affects the fracture surface morphology of Grade 91 ferritic steels. In a different operating condition of P91 steel, different microstructures formed. Generally in supplied state, it contains the tempered martensite with $M_{23}C_6$ and fine MX precipitates captured along the prior-austenite grain boundaries (PAGBs) and grain interior region [7–9,12].

The present research work deals with the study of the fracture surface morphology of C&F Grade 91 specimen after room temperature impact and tensile testing in different heat treatment conditions. The material is supplied by the Bharat Heavy Electricals Limited (BHEL), Haridwar, India. The material is supplied in the C&F condition.

2. Experimental details

The experiments were performed on the C&F plate ($300 * 150 * 60$) of the Grade 91 (X10CrMoVNNB9-1) steel. The chemical composition and mechanical properties of C&F Grade 91 steel in as-received condition are depicted in Table 1 and Table 2, respectively. From the as-received thick plate material small samples with a dimension of $(150 * 50 * 12)$ mm^3 were cut. After sectioning the samples were normalized at 1040 °C for 40 min followed by air cooled. After normalizing the samples were subjected to various heat treatment regimes as per Table 3.

The heat treatment on the samples was performed in Laboratory furnace. The furnace is used under the protective powder mixture of Al_2O_3 and FeCr. After thermal heat treatment, tensile and impact specimen were prepared according to the required dimension. The Vickers hardness tester (Omnitech-S. Auto) was used to perform the hardness measurement of as-received C&F

Table 2
Mechanical properties of cast and forged Grade 91 steel in as-received state.

	Yield strength (MPa)	Tensile strength (Mpa)	Elongation (%)	Hardness (HV)	Toughness(Joules)
C&F Grade 91 steel	455 ± 10	655.5 ± 6.4	22.1 ± 0.2	231 ± 5.4	96 ± 5
Min requirement	Min 450	600–750	Min 15	–	Min 30

Table 3
Different heat treatment regimes performed on cast and forged Grade 91 steel, investigated in present study.

Material state	Microstructure	Heat treatment
As-received (AR)	Partially tempered martensite	Cast and forged (C&F)
Air cooled (AC)	As quenched martensite	AR + austenitizing at 1040 °C for 40 min, air cooling
Heat treated at 350 °C and air cooled (HT350)	Tempered martensite (partially)	AC + tempered at 350 °C for 2 h
Tempered at 650 °C and air cooled (T650-AC)	Fully tempered martensite	AC + tempered at 650 °C for 2 h
Tempered at 760 °C for 2 h and air cooled (T760-2-AC)	Fully tempered martensite	AC + tempered at 760 °C for 2 h
Re-austenitized at 1000 °C and air cooled (r-A1000-AC)	As quenched martensite	AC + tempered at 1000 °C for 2 h
Tempered at 760 °C for 2 h and furnace cooled (T760-2-FC)	Fully tempered martensite + ferrite	AC + annealed at 760 °C for 2 h, furnace cooled
Tempered at 760 °C for 4 h and air cooled (T760-4-AC)	Fully tempered martensite	AC + tempered at 760 °C for 4 h
Tempered at 760 °C for 6 h and air cooled (T760-6-AC)	Fully tempered martensite	AC + tempered at 760 °C for 6 h
Tempered at 760 °C for 8 h and air cooled (T760-8-AC)	Fully tempered martensite	AC + tempered at 760 °C for 8 h