INFLUENCE OF JOINT DESIGN & WELDING VARIABLES ON ETP COPPER

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INTRODUCTION

Copper is second only to iron and steel in commercial application and offers a unique combination of properties among which the most important are electrical and thermal conductivity, strength, corrosion resistance, wear resistance, spark resistance and the last but not the least is its non-magnetic behaviour [1,2]. Apart from silver, the copper has highest electrical and thermal conductivity amongst all the metals and is extensively used in making electrical conductors, radiators, heat exchangers; condensers and machine parts [4]. Electrolytic Tough Pitch (ETP) copper is the most important type of copper and is frequently used for high electrical conductivity applications because of its easy commercial availability and more uniform electrical and mechanical properties [5]. A Short Circuit (SC) ring of ETP copper shown in Fig. 1 is an essential part of induction motor used for carrying the rotor current. The size and thickness of SC rings depends upon the capacity of individual machine and is generally manufactured by forging. It is well known that forging is a costly and time-consuming process. It is also noteworthy to mention that one may have apprehension of high percentage of rejection due to forging defects and discontinuities. To mitigate the above problem, the Scientists of RRL (CSIR), Bhopal and the Engineers of BHEL, Bhopal jointly undertook an R&D programme to fabricate SC rings by welding and to study welding technology aspects of ETP copper.

The main objectives of the present investigation are as follows :

- Selection of welding process
- Optimization of process variables for different thickness
- Optimization of weld joint design
- Transfer of technology for the production shop floor.

WELDABILITY OF ETP COPPER

Weldability is a complex property of materials. Therefore it can not be defined uniquely by a single factor for most of metals, including ETP copper [6]. The weldability factors of ETP copper discussed in this paper are:

- Inherent Characteristics of Material
- Technology Selection
- Weld Joint Design.

Inherent Characteristics of Material

ETP copper contains about 0.06% of oxygen as gas or in the form of cuprous oxide, which causes porosity

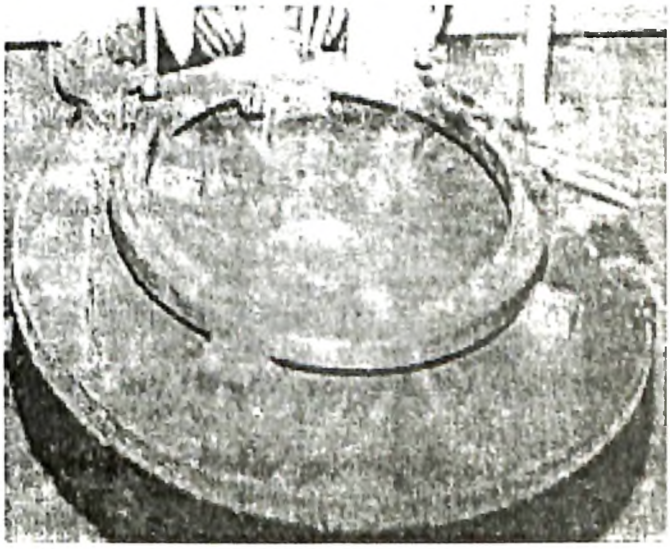

Fig. 1. Short Circuiting Ring in welding fixture.

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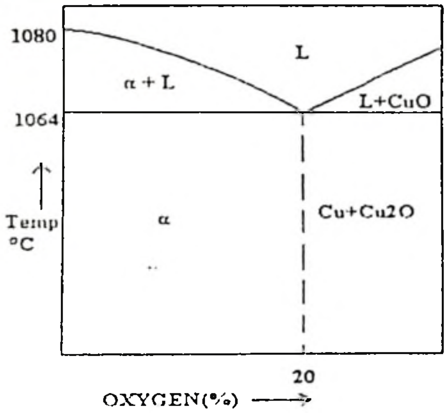

Fig. 2. Cu : Cu_2O Diagram.

in weldment. The weld joint efficiency of fusion arc welded joints made of ETP copper generally depends on the actual amount of cuprous oxide present [7,8]. In copper, cuprous oxide (Fig. 2) is scattered more or less uniformly throughout the wrought matrix and has no harmful effect on the mechanical and electrical properties of the base metal.

As the ETP copper is heated up during the welding, the cuprous oxide gets converted to cupric oxide and very reactive atomic oxygen, as shown in the following equations:

$$Cu_2O \xrightarrow{\Delta} CuO + Cu \quad \text{------ (i)}$$
$$2CuO \longrightarrow 2Cu + O_2 \quad \text{------ (ii)}$$
$$O_2 \longrightarrow (O) + (O) \quad \text{------ (iii)}$$

After welding, the molten metal solidifies very quickly, causing entrapment of the oxygen, which leads to sub-surface porosity. It is juxtaposing to note that though high heat and temperature is the reason to form detrimental copper oxide, even then it is necessary to give high preheat to copper during welding to combat heat transfer and to achieve good fusion.

In addition to above problems, due to the presence of hydrogen from shielding gas, moisture and unclean base metal surface, a steam reaction is likely to occur in the ETP copper.

$$\underset{\text{(Dissolved in copper lattice)}}{2H + Cu_2O} \longrightarrow \underset{\text{(Gas)}}{2Cu + H_2O}$$

EXPERIMENTATION

Attempts were made to optimise the various factors which influence the weldability of ETP copper, *viz.*, process, technique, type of filler metal, welding parameters, weld joint geometry, pre and post weld heat treatment, shielding environment, etc.

Technology Selection

At initial stage of trial, both Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) were selected as welding process but at later stage, the experimentation was carried out using GMAW because of high productivity and unsuitability of GTAW process for thicker sections. GTAW process was also replaced with GMAW in few other applications like welding damper bars of large industrial rotors. Breakthrough advantages like excellent fusion, reduced preheat; reduced operator fatigue and major reduction in cycle time were noticed.

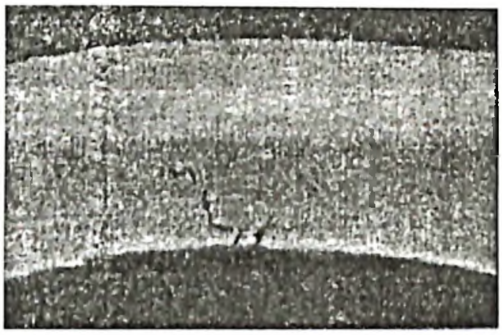

Fig. 3. Weld Centre Line Cracking

In GMAW the process variables such as current, voltage, wire feed rate, wire size and shielding gas have remarkable influence in obtaining radiography quality welds. Variation in these parameters were minimised by using a synerigic GMAW process in which a special copper-welding programme was developed and installed in the machine using EPROM chips. Controlled heat input combined with repeatability of parameters in above setup helped in reducing defect rate.

Composition of the filler wire has been observed to seriously affect the weld metal soundness. Pure copper filler wires with insufficient deoxidants have been found to produce centre line cracks in the weld metal (Fig. 3).

Pre-weld cleaning is found highly essential to improve radiography quality. Surface oxide formation could be minimized by smearing a flux (72% boric acid powder, 15% anhydrous sodium phosphate and 13% sodium chloride) on the prepared edges. Impurities and moisture in the shielding gas increased porosity in the weld metal. Therefore argon gas with minimum purity of 99.9978% has been found to be suitable for the application. Argon-Helium gas mixture (75-25) was used on few jobs. In this case the preheat of 450°C (against 600°C in case of Argon) was sufficient to get good weld metal fluidity and fusion. However, this choice had to be abandoned because of prohibitive cost and irregular supplies.

Weld Joint Design

A rigorous study was conducted to investigate the effect of change in weld joint design on the joint integrity. The weld joint is primarily designed to get proper welding approach and meet the job design requirement. Besides, the joints should be designed to avoid stress concentration and to obtain the optimum pattern of residual stress distribution. In order to obtain the desirable weldments property data for ETP copper test pieces, different types of weld joint with various combination of groove and gradients were considered during the experimentation. The weld joint and its essential details for 20 mm thick sections are shown and illustrated in Fig. 4 and Table 1, respectively.

Prior to the edge preparation the copper was subjected to chemical analysis and mechanical testing. A number of trial pieces of size 20 mm × 50 mm × 150 mm were prepared by machining.

In order to hold molten metal, the suitable type of non-consumable backing strips were incorporated at the weld zone.

All the joints were then examined visually and subjected to Destructive and Non-Destructive Examination to evaluate the integrity and quality. To assess the mechanical properties, the prepared specimens were tested using a Universal Tensile Machine (Instron Mode No. 1185). The fractrographic analysis of the tensile tested specimens was carried out using Scanning Electron Microscope (SEM Model No JOEL 35), for a comprehensive understanding about the nature of the fracture. To assess the

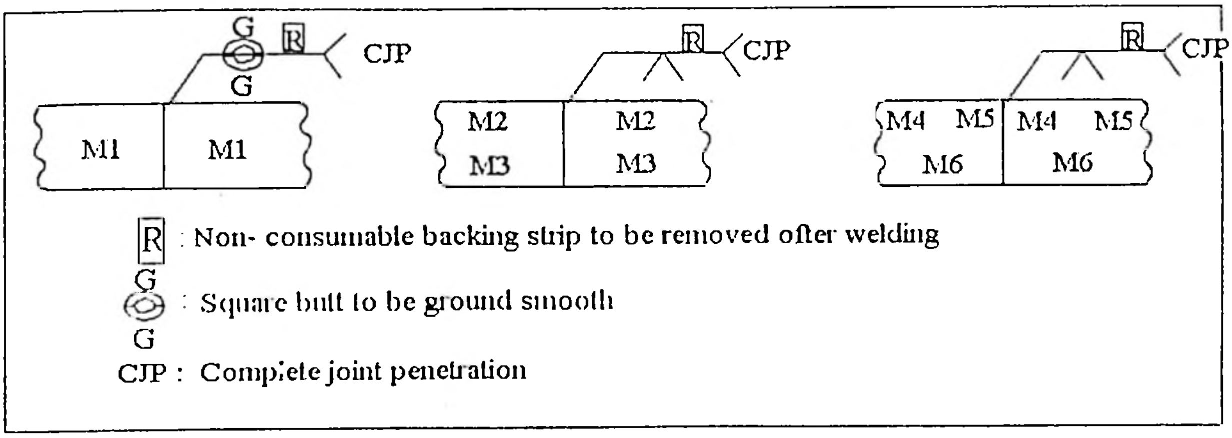

Table 1. Details of Weld Joints

Joint Code	No. of Joints	Root Opening (mm)	Gradient		Filler Metal (gms)	Remarks
			8	8		
M_1	2	20	NA	NA	179.0	Square butt
M_2	3	Approp.	45	60	87.8	Double grad.
M_3	2	-do-	30	45	66.2	-do-
M_4	1	-do-	90	NA	162.9	Single grad.
M_5	5	-do-	60	-do-	99.5	-do-
M_6	2	-do-	45	-do-	76.7	-do-

The process variables used for each weld joints are listed in Table 2.

Table 2. Details of Process Variables for Each Joints

Sl.No.	Joint Code	Joint No.	Pre-heating Temp (°C)	Current (A)	Voltage (V)	Argon (L/min)	Cooling
1	M_1	M_{11}	650 (Spot)	310.0	27.9	24.0	Air
		M_{21}	600 (Uniform)	323.0	31.4	23.0	Slow
2	M_2	M_{12}	700 (Uniform)	338.0	32.2	25.0	Air
		M_{22}	600 (Spot)	347.0	33.3	23.0	Slow
		M_{32}	650 (Uniform)	325.0	31.6	24.0	Air
3	M_3	M_{13}	700 (Uniform)	325.0	31.5	24.0	Air
		M_{23}	600 (Uniform)	314.0	29.6	25.0	Air
4	M_4	M_{14}	700 (Uniform)	350.0	34.0	23.0	Air
5	M_5	M_{15}	600 (Uniform)	326.0	31.9	19.0	Air
		M_{25}	700 (Spot)	316.0	30.1	22.0	Slow
		M_{35}	550 (Uniform)	337.0	32.1	24.0	Air
		M_{45}	650 (Uniform)	325.0	31.5	23.0	Air
		M_{55}	650 (Uniform)	315.0	29.8	25.0	Air
6	M_6	M_{16}	650 (Uniform)	315.0	29.7	24.0	Air
		M_{26}	700 (Uniform)	312.0	28.0	25.0	Slow

metallurgical factors influencing the properties of weldment and Heat-Affected-zone (HAZ), metallographic analysis were conducted using LEITZ Optical Microscope in accordance with the standard metallographic practice.

RESULTS AND DISCUSSION

The result of the various quantitative and qualitative tests conducted for weldment, HAZ and the parent material, are discussed in the following sections:

Non-Destructive Examination

Visual examination followed by Liquid Penetration Test (LPT) on the welded joints revealed no surface defects of discontinuities. The subsequent Radiographic Examination (RE) revealed that weld joints with acceptable level of porosity were produced, when all the weld procedure conditions were satisfied except weld joint M_{11} and M_{21}. In those cases where operational interruptions, such as stoppage in filler wire feed, stoppage and leakage of shielding gas as well as under-filling of the filler metal, etc., occurred during welding, gas-related porosities are caused. The records of the radiographic examinations of three weld joints are shown in Fig. 5. Porosity revealed in the case of the joint M_{13} is attributed to the corresponding interruption. In the case of the weld joint, M_{11} although no operational interruption was recorded, aligned porosities along the fusion boundaries have been noticed in RE. This may be attributed to faulty weld joint design causing inadequate shielding at the fusion boundaries or poor accessibility or both.

Tensile Test

The specimens were prepared by machining of the transverse cut section of the weld joints as per

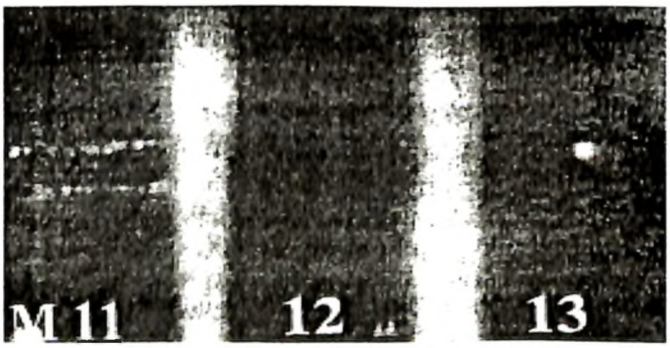

Fig. 5. Records of RE of three weld joints.

requirements of ASTM standard. The results obtained from the tests are given in Table 3.

It can be observed from the results that in most of the cases of "V" groove weld joints, the Ultimate Tensile Strength (UTS) values are acceptable to design requirement and much higher than those obtained in the case of the square butt type of weld joints. However, in either case the weld joint strength was lower than that of the parent material. It was also observed that both the weld joints of square butt type were fractured from the weldment, indicating poor quality of welding, but in the case of "V" groove weld all the specimens broke away from the joints as generally happens when the welding is sound. Fig 6 shows the tensile test fracture specimen with "V" groove of joint. It has been also demonstrated by tensile tests that scattered blunt flow (*i.e.*, porosity, in this case) has no significant effect on the tensile strength of "V" groove type weld joints. This might have resulted from fact that the pores are not aligned in single plane.

Fig. 6. A tensile tested specimen.

Fractographic Analysis

The fractured surface of tensile tested specimens were examined under the SEM. Fractrography revealed a typical ductile fracture in the case of "V" groove type of joints, and indicates that these fractures are similar to those observed in the case of the parent ETP copper. This analysis also reveals that the presence of scattered porosities in weldment has not significantly altered the strength of the joints. This is further supported by the high joint efficiency values (up to

Table 3. Assessed Mechanical Property Data

Sl. No.	Joint No.	Type of Weld Joint	Backing Strip	Root Opening (mm)	UTS Value (MPa)	Joint Efficiency (%)	Elong. at 50 mm (%)
1	M_{11}	Sq. Butt	NC	20	120.0	52.40	31.21
2	M_{21}	-do-	NC	20	108.0	47.16	29.09
3	M_{12}	V-groove	designed	3-5	210.0	91.70	35.64
4	M_{22}	-do-	-do-	-do-	194.0	84.72	34.05
5	M_{32}	-do-	-do-	-do-	186.0	81.23	—
6	M_{13}	-do-	-do-	-do-	181.0	79.04	33.17
7	M_{23}	-do-	-do-	-do-	168.0	73.36	—
8	M_{14}	-do-	-do-	-do-	165.0	72.05	32.29
9	M_{15}	-do-	-do-	-do-	186.0	81.23	34.28
10	M_{25}	-do-	-do-	-do-	192.0	83.84	33.91
11	M_{35}	-do-	-do-	-do-	169.0	73.78	—
12	M_{45}	-do-	-do-	-do-	188.0	82.10	33.28
13	M_{55}	-do-	-do-	-do-	184.0	80.35	33.29
14	M_{16}	-do-	-do-	-do-	142.0	62.48	—
15	M_{26}	-do-	-do-	-do-	167.0	72.93	32.54

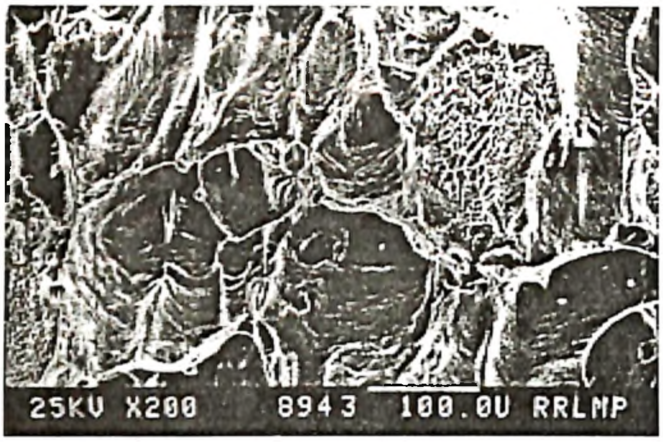

Fig. 7. SEM Micrograph of fractured surface.

92% in the case of M_{12} joints) obtained in this study. In Fig. 5, a sizable porosity can be clearly seen in the centre of the weldment in the case of M_{13} joints, but the efficiency of this joint is approximately 79%, which is considerably high. In contrast, in the case of steel, porosity of equivalent size would have significantly reduced the efficiency. SEM micrograph of the fractured surfaces of M_{45} joint is shown in Fig. 7.

Macro and Microstructural Analyses

Some of the weld joints were cut and polished, and the specimens were then prepared for macro and microscopic examinations using the standard metallographic practice, to understand the changes that occurred in the weldment, HAZ and the parent metal due to the heat evolved during welding. Macrostructure of transverse cross-section at HAZ of defective welds M_{11} shows coarse-grained structure with gross porosity & copper oxide inclusions (Figs. 8 & 9).

The micro-structural analysis of M_{12} weld joint has clearly shown the solidification structure of the filler metal, in the form of long columnar grain near the

Fig. 8. Coarse - grained dendritic structure of weld metal (75X).

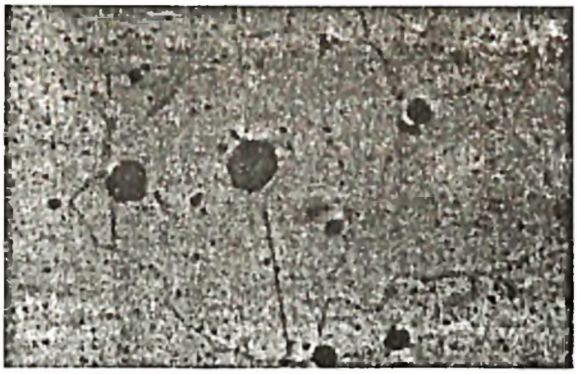

Fig. 9. Coarse grain structure with gross porosity (150X).

fusion boundary and equiaxial grains in the centre of the weld bead. HAZ could not be visually observed because ETP copper does not undergo phase transformations like steel. Fig. 10 shows a photograph of the fusion boundary. It is interesting to note the way in which the growth of columnar grains in the weld developed directly from the grains of the parent material adjacent to the fusion line. This type of grain growth is known as epitaxial. Up to a certain extent, such growth helps to improve the tensile strength of the material. The analysis also clearly reveals that the size and number of pores per unit area are more in the region that received less heat.

A similar type of investigation was undertaken for 30 mm, 40 mm, 50 mm and 60 mm thick sections and the established process specifications transferred for the shop floor practice for regular production of SC rings.

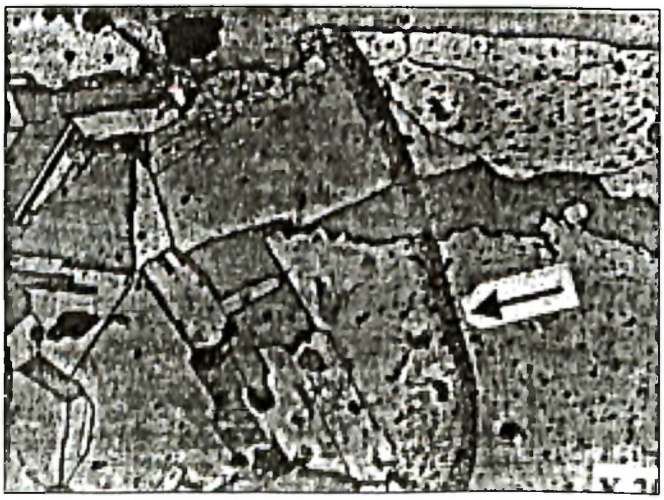

Fig. 10. Photomicrograph of fusion boundary.

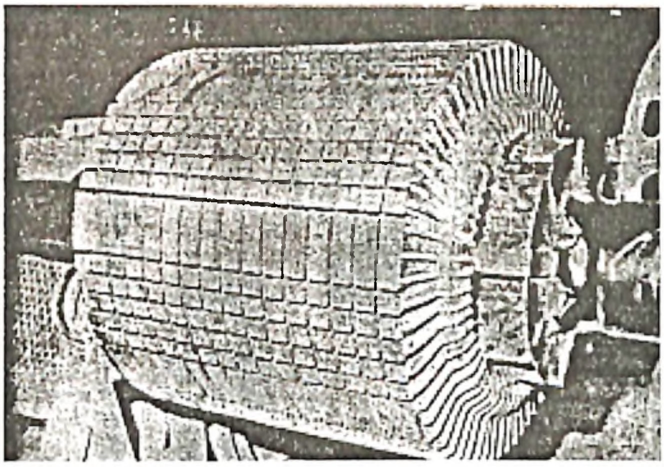

Fig. 11. Large electrical rotor with damper bars.

Understanding welding technology and behavior of ETP coppers in SC ring welding assisted in developing manual & automated welding of more complex jobs like damper bar welding in rotors of large industrial & traction motors refer Fig. 11.

CONCLUSION

Sound weld joints can be produced in the case of thick section of ETP copper using GMAW process provided the weld joints is adequately designed and the process variables are optimized. "V" groove types of joints are much better suited than the square butt type weld joints for producing radiographic quality welds. The surface cleanliness and the pre-heating temperature of about 65°C are the most important factors to produce sound welds. Accidents during welding should be minimized to achieve uniformly good weld quality, and the welding operation should be completed in one sitting. Scattered porosity in element does not proportionally affect the tensile strength of weld joints. The size and number of pores per unit area are more in the region that receives less heat. Therefore, pre-heating should be sufficient and uniform throughout the metal. The grain growth in weldment is the epitaxial in nature, which has probably helped in improving the tensile property, in spite of the porosity.

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WELDING OF COPPER...

Corrosion Behaviour

Copper is frequently used metal in the potable water supply systems, heat exchangers, etc., because of its excellent corrosion resistance. Though the water in contact with the material is fresh and seems to be harmless, cases of pitting are common. In such case, an increase in free corrosion potential was seen. However, Microbiologically Influenced Corrosion (MIC) was suspected in the corrosion failure of heat exchanger copper piping, carrying ground water. It is also well known that copper is toxic in nature. So the MIC on copper weldments leads to the conclusion that, microbes can grow and multiply even in the presence of toxic copper ions.

Conclusion

There is a growing interest in welding of copper and copper alloys. In order to obtain desire weld quality, the behaviour of the materials in terms of physical, mechanical and metallurgical properties should be considered so that proper welding procedure could be developed.

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