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WELDING OF THIN MOLYBDENUM SHEETS BY EBW AND GTAW

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Abstract: *Two welding technologies (EBW, GTAW) were used to weld thin Mo sheets. Sheets thick 0.2 mm were welded by EBW and 0.4 mm thick samples were welded by GTAW welding methods. Welds were tested by means of metallography, optical microscopy, hardness measurement, chemical analysis etc. Mo welding is difficult because of inherently low ductility of Mo and high affinity to oxygen. Experiments proved that EBW is much better for welding thin Mo sheets, because it is done in vacuum and has much lower heat input. HAZ width of EBW was 1.4 mm compared to more than 35 mm for GTAW weld.*
Keywords: *Molybdenum, EBW, GTAW, Welding, Micro-hardness*

1. INTRODUCTION

Molybdenum is a refractory metals that is used for special applications for high temperature use as aircragt parts, holders of tungsten filaments, anodes, heating elements of furnaces etc. One of interesting application is vessels for high temperature furnace remelting of glass and gemstones. For such an application thin Mo sheets are to be welded to create vessel of specific shape. To research welding of thin Mo sheet with the aim of creating vessel is purpose of this research.

2. EXPERIMENT

Thin rolled pure Mo sheets of thickness 0.2 and 0.4 mm were welded by gas tungsten arc welding (GTAW) and electron beam welding (EBW). Experiments done include tensile strength testing with machine LabTest, chemical analysis was done by XRF spectrometr Olympus Delta, Vickers hardness HV0.5 was measured by IndentaMet 100 and metallographic observation done by optical microscope Carl Zeiss AxioObserver 1Dm.

3. BASE METAL

Molybdenum (Mo) is refractory metal, with melting point 2620 °C. Compared to other refractory metals it has lower density, 10.2 g/cm^3) and low coefficient of thermal expansion, 4.8.10^{-6} m/mK. Mo crystallizes in BCC lattice [1]. Molybdenum has low ductility and is produced by powder metallurgy. The product is influenced by purity of Mo powder and production process. It`s Brittle-ductile transition temperature is around room temperature.

Typically rods, wires produced by powder metallurgy are widely available. But in our research thin Mo sheets produced by PM followed by rolling were used. Base material sheets were tested by tensile strength test and the results are in Tab. 1.

Thickness [mm]	Young modulus E [GPa]	Yield strength R_p [MPa]	Ultimate tensile strenght R_m [MPa]	Ductility A_{80} [%]	Hardness [HV0.5]
0,2	79	1214	1530	0.9	320
0,4	48	759	968	2.3	280

Tab. 1. Tensile strength test results for base material

As visible, the Mo sheets have very low ductility, 1-2 %, so no drawing or sheet metal working is possible (the vessel forming by deep drawing is not possible), so welding needs to be used. Even when flanging and bending was used as preparation of semiproduct before welding, cracks were created at the edges. The band structure of base metal is seen at metallographic macrographs at fig. 1, 2.

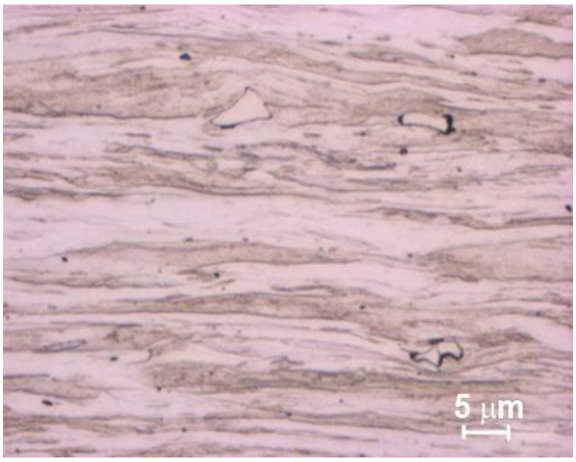

Fig. 1. Macrograph of Mo base metal 0.2 mm structure

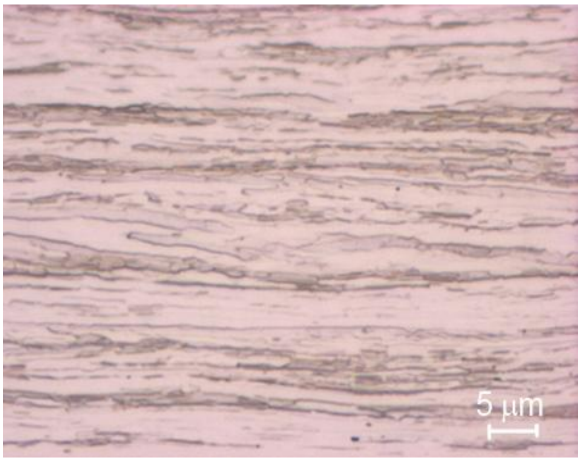

Fig. 2. Macrograph of Mo base metal 0.4 mm structure

Using XRF analysis chemical compostition as in Tab. 2 was found out. The both samples contain significant volume of phosphorus that is known to decrease ductility significantly in many metallic materials, e.g. steel and is bad for welding.

Thickness	Mo [%]	P [%]	W [%]
0.4 mm	97.65	2.35	-
0.2 mm	97.35	2.31	0.34

Tab. 2. Chemical compostition of BM

4. MOLYBDENUM WELDABILITY

Molybdenum has certain properties that render its weldability difficult.

Low ductility causes problems, when thermal expansion and deformation. High notch sensitivity of Mo is also demanding weld surface to be smooth.

Mo has high affinity to oxygen, nitrogen, carbon. Over 400°C MoO_2, low melting, brittle compound, over 1100°C molybednium nitrides are created. Welding needs to be done in inner shielding gas of high purity (Ar, He). At best vacuum chamber would be used [2]. Carbides, oxides, nitrides segregate at the grain boundaries, the weld metal (WM) ductility is decreases.

Welding of Mo causes grain coarsening, i.e. loss of mechanical properties over recrystallization temp 900°C.

From fusion welding techniques GTAW, EBW, LBW can be used. Closed chamber Ar shielding to prevent oxidation is necessary. High power density is preferable, as laser and electron beam to minimize heat input.

From pressure welding techniques friction stir welding FSW, friction welding FW, resistance welding RW can be used

5. ELECTRON BEAM WELDING (EBW)

EBW is based on transforming kinetic energy of free electrons into heat upon impinging on base material [3].

Electrons are emitted from heated catode. Kinetic energy is supplied by strong electric field. Electron beam is focused and guided by magnetic fields.

5.1 used equipment for EBW

EBW welding was done in cooperation with Nuclear Research Institute Řež a.s. at welder EBW-HC, it`s parameters in Tab..3.

Voltage	60 kV
Max. welding current	80 mA
Max. power	4,8 kW
Vacuum	up to 2 x 10^{-5} mbar
Welding chamber - inner	490 x 490 x 490 mm

Tab. 3. Parameters of electron beam welder EBW-HC

5.2 Welds and welding parameters

At first square butt welds of 0.2 mm sheets were done with beam focused at the gap. The butt welding of thin sheets proved to be unsuccessful, because of irregular weld. For such thin sheets square butt joint is unusable. Nextly sheets were ovelaped 5 mm and fillet welded lap joint and through-welded lap joints were done and successfully welded, as at fig 3.

Welding speed and voltage were constant, speed v = 10 mm/s, voltage U = 60 kV. Current, lap weld position and focal distance was varied, as in Tab. 4.

Weld sample	Weld position	I [mA]	Focal distance [mm]
1	Sheet edge	6	550
2	Sheet edge	6	555
3	Sheet edge	6	560
4	3 mm from sheet edge	6:5	560

Tab. 4. Parameters used for EBW process optimization

Samples 1 to 3 were weldied with fillet lap joint and sample 4 with through-welded lap joint, as at fig. 3.

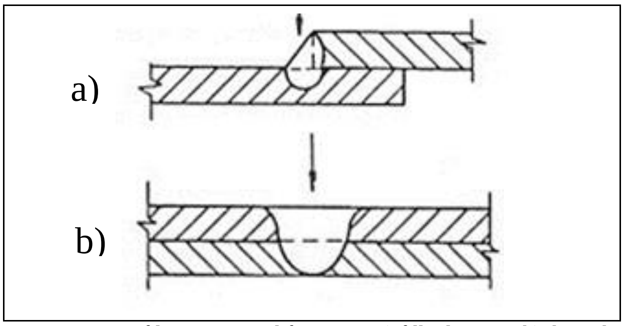

Fig. 3. Design of lap joints used for EBW- a) fillet lap joint b) through-welded lap joint

6. GTAW WELDING

This arc welding method uses nonconsumable tungsten electrode. Molten pool and electrode are protected by innert shielding (mainly Ar) gas. GTAW process offers superior arc control, less spatter, smaller heat input, compared to other arc welding technologies (MMA, GMAW) and is often used for thin materials, alloyed and stainless steels. Al alloys can be welded using alternate current.

Sheet 0.4 mm thick we assembled in corner joint and welded without using filler wire, as at fig. 4. Selected electrode diameter was 1.2 mm and welding parameters according to Tab. 5.

Current [A]	Current / polarity	Voltage [V]	Welding speed [mm/min]	Gas	Filler wire
20	DC / -	10.5	50	Ar 6.4	none

Tab. 5. Parameters used for GTAW welding

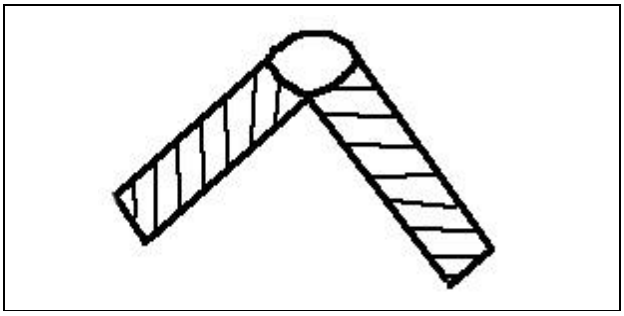

Fig. 4. Corner joint

7. RESULTS

EBM welded lap joints are without oxides as at fig. 5. Measured weld and HAZ width is in Tab. 6. No cracks were found in WM or HAZ, because of small width of weld and HAZ together with welding in vacuum.

Sample EBW	1	2	3	4
Weld width [mm]	0.64	0.80	0.68	0.62
HAZ width [mm]	1.1	1.4	1.1	1.4

Tab. 6. Weld and heat affected zone (HAZ) width

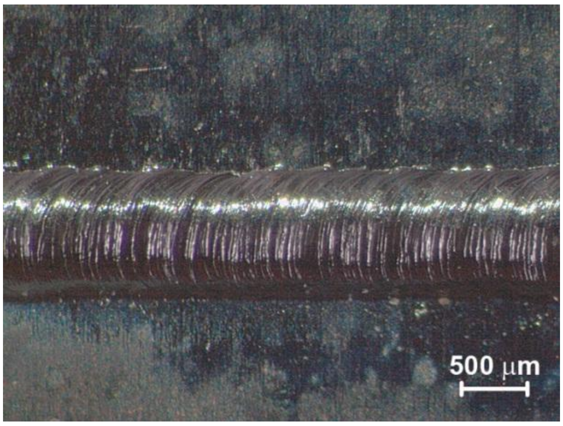

Fig. 5. Sample welded by EBM

Metallographic macrographs of EBM welds are at fig. 6 – 8. Sample EBW 1, 2, 3 were welded with same current 6 mA and welding distance was increased from 550 mm, to 555, 560 mm. By this, weld width did increase and weld face reinforcement decreased with it. From the point of view of weld shape, the sample 3 is the most suitable

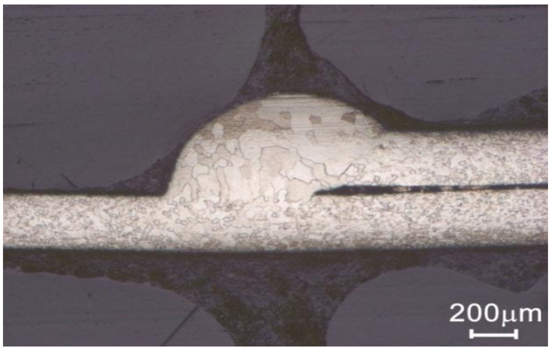

Fig. 6. Metallographic macrograph EBW 1

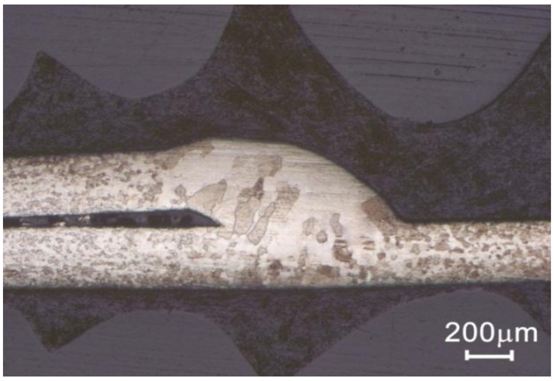

Fig. 7 Metallographic macrograph EBW 2

For sample EBW 4, weld-through lap weld, current 6.5 mA and focal distance were used. Weld pool sagged and resulting weld has underfill, because of sheets gap.

Macrograph of GTAW weld is at fig. 9. Weld size and HAZ are at Tab. 7. Because of limited size of welded sheet (width 35 mm), heat input of the GTAW is so big that all the sample was heat affected.

Fig. 8. Metallographic macrograph EBW 3

Sample	GTAW
Weld bead width [mm]	1.70
HAZ width	over 35 mm

Tab. 7. GTAW weld bead and HAZ width

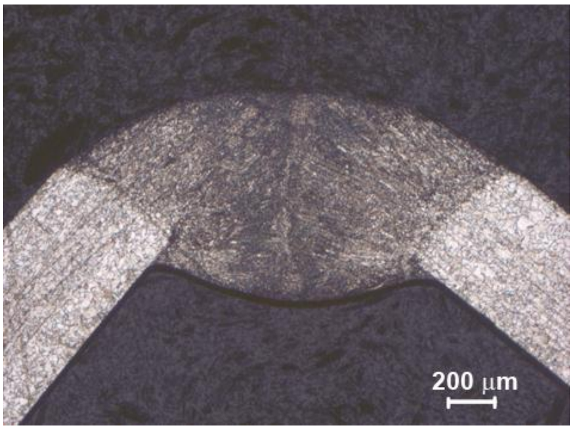

Fig. 9. Metallographic macrograph of GTAW weld

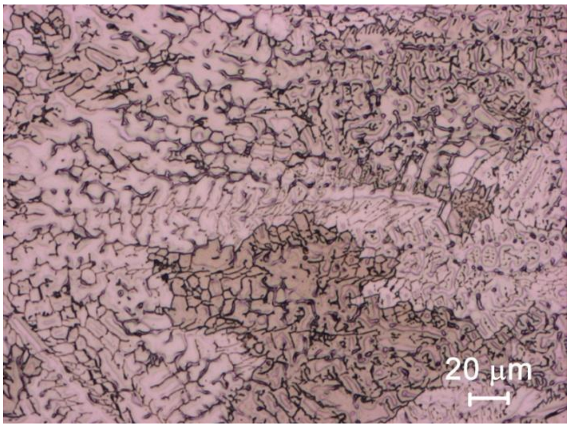

Fig. 10. Weld metal microstructure of GTAW weld, mag. 200x

There were no inner defects found in the welds. Micrographs are at fig. 1, 2 for base metal, at fig. 10 to

13 are from welded samples. Obviously welding did cause recrystallization of BM molybdenum. Fig. 10 shows cast like grain structure, caused by big heat input of GTAW. Big irregular grains (40-140 μm) with dendrites are present in weld metal, in HAZ there are polyedric grains of size 10-40 μm with visible twins.

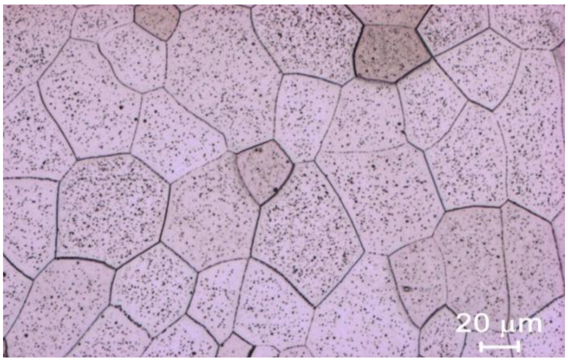

Fig. 11. Weld metal microstructure of EBM weld, mag. 200x

Microstucture of EBW samples is at fig. 11 and 13. WM is composed by regular polyedric grains with size 20-40 μm. HAZ zone composes from grain of various size 5-30 μm.

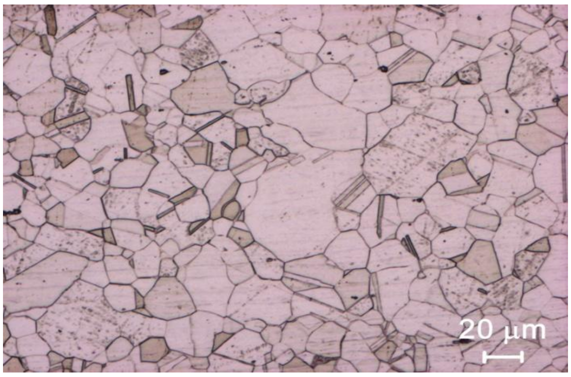

Fig. 12. HAZ microstructure of GTAW weld, mag. 200x

Difference of EBW and GTAW microstructure is very different in grain size and shape. In WM area GTAW weld is crystallizing in columnar dendritic morphology. EBM weld crystallizes in cellula morphology, because of much higher temperature gradient, when cooling.

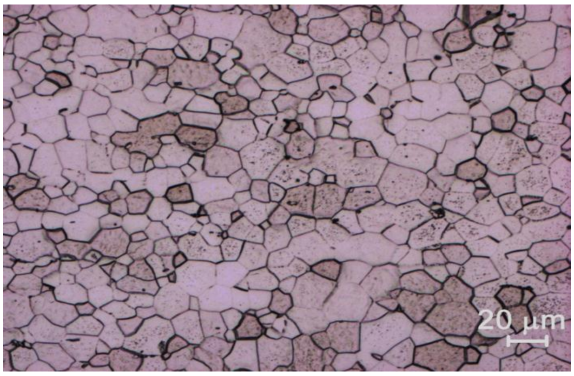

Fig. 13. HAZ microstructure of EBM weld, mag. 200x

Hardness measurements according to Vickers with 500 g are shown at graphs fig. 14, fig. 15. Hardness of BM was about 320-350 HV. There is obvious decrease caused by welding for both methods. Minimum hardness was measured in WM and adjacent HAZ, where hardness 160 HV0.5 was measured for both methods. The HAZ width of EBW weld is much narrower than GTAW.

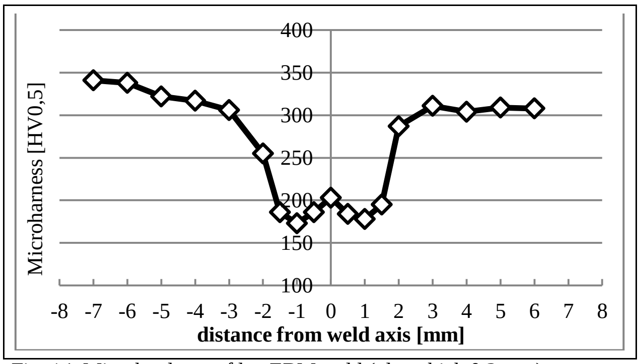

Fig. 14. Microhardness of lap EBM weld (plate thick 0.2 mm)

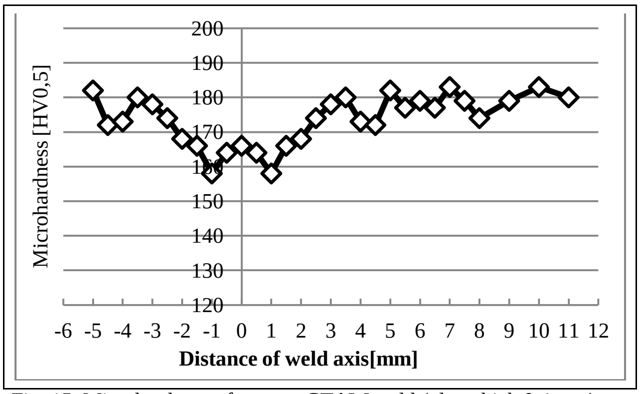

Fig. 15. Microhardness of corrner GTAW weld (plate thick 0.4 mm)

8. CONCLUSION

Two welding methods, EBW and GTAW, for welding molybdenum thin sheets were used and optimized. All welds were without inner defects or voids, so they were accepTab. according to norm ISO 5817. Most problems of welding molybdenum are caused by the inherently low ductility of molybdenum, where our supplied samples had ductility in range 1-2 %. Electron beam welding is advantageous compared to GTAW, when microhardness, microstructure and welding speed are compared. This is caused by high heat density of EBW, i.e. heat input of EBW is tenths of times smaller. Obviously EBW should be the chosen welding technology for moluybdenum.

9. ACKNOWLEDGEMENT

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