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# Rotary friction welding of molybdenum components

M. Stütz[a,*], F. Pixner[a], J. Wagner[b], N. Reheis[b], E. Raiser[c], H. Kestler[b], N. Enzinger[a]

[a] IMAT, Graz University of Technology, Austria
[b] Plansee SE, 6600 Reutte, Austria
[c] Klaus Raiser GmbH & Co. KG, Germany

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## ABSTRACT

Joining of TZM components by inertia rotary friction (IFW) welding is an established industrial process for welding cross-sections up to 1500 mm$^2$. Up-scaling to medium-size components up to 5000 mm$^2$ in a direct drive friction welding process requires a better understanding of the influencing factors of the weld procedure, e.g. machine parameters, weld preforms, and the clamping system. Based on the existing IFW process for TZM tubes, welding parameters were transferred to tubular components of pure molybdenum (OD: 150 mm, ID: 130 mm, 4400 mm$^2$). Successful welds were produced showing a fine-grained, defect-free microstructure. However, molybdenum proved to be more challenging than TZM. Particularly high upset rates and motor overload occurred during the friction phase. Therefore, a study was carried out to reveal the underlying mechanisms with small-size samples under laboratory conditions. It was shown that extensive plastic deformation of the entire weld zone occurred due to higher thermal diffusivity and lower strength of molybdenum compared to TZM. This high upset rate reduces the process window for a reproducible welding procedure significantly. In conclusion, a concentrated energy input during the transition from friction to forge phase is required to countervail the high thermal diffusivity of molybdenum. Based on these observations, the feasibility of friction welding of medium-size molybdenum tubes will be discussed.

## 1. Introduction

Rotary friction welding (RFW) is a solid state joining process, where the required heat is generated by friction between the joining partners. When the shear strength is reached, plastic deformation occurs and the characteristic weld flash starts to form. In general, two concepts exist: inertia friction welding (IFW) and direct drive friction welding (DDFW). In IFW the rotary part and an attached flywheel are accelerated, then the drive is decoupled and the welding partners are brought in contact. The speed of the parts decelerates during the whole welding process continuously. Towards the rotary halt, the axial force is increased. In direct drive friction welding (DDFW), a motor drives the rotary welding part during the whole process and at the braking of the rotation, the axial pressure is increased whereby the flash is fully formed and the process is completed shortly after the spindle halt. Based on the historical development of the friction welding process, IFW is mainly used in North America, while in Europe DDFW is predominant [1–3].

Molybdenum is a refractory metal and shows unique properties, such as high melting point, high thermal conductivity and low thermal expansion coefficient. However, Mo is brittle at room temperature and highly susceptible to brittle failure due to impurities, most of all oxygen [4]. Therefore, minimizing impurities is an aim in the production of Mo and Mo-based alloys [4,5]. The dispersion strengthened alloy TZM is the most used Mo-alloy. Small additions of titanium, zirconium, and carbon lead to the formation of carbides and act as getter elements for oxygen. As a further consequence, recrystallization temperature and high temperature strength are increased compared to technical pure Mo [4]. In the temperature range between 900 °C and 1500 °C the ultimate tensile strength (UTS) of TZM is up to five times higher compared to Mo, and the service temperature for TZM is specified up to 1400 °C [6].

Mo and Mo-base alloys generally exhibit limited weldability. Fusion welding of molybdenum and TZM causes an embrittlement of the heat affected zone due to grain coarsening and precipitated impurities at the grain boundaries [7,8]. In contrary, the technique of friction welding avoids the typical defects of fusion welding and the resulting embrittlement. Since the grain size is reduced by high deformation and deformation rates during the process, the strength and toughness are improved compared to fusion welding processes [9,10]. An example for the industrial application of friction welding is the manufacturing of TZM target-stem assemblies for X-ray tubes. IFW is used to join these TZM-components, where the weld energy is provided by the rotating flywheel. Typical cross-sections are in the range up to 1500 mm$^2$ TZM

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[*] Corresponding author.
*E-mail address:* markus.stuetz@tugraz.at (M. Stütz).

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[10,11].

The aim of this work is to weld pure molybdenum tubes with cross-sections up to 5000 $mm^2$ on a DDFW-machine. Process parameters were investigated based on the experience with IFW of TZM. However, previous investigations have shown that DDFW of Mo is challenging. Preliminary spindle halt, insufficient drive power and clamping problems occurred. A detailed parameter study was not possible [12]. Hence, experiments with small samples of Mo and TZM were investigated under laboratory conditions in order to:

- Identify reasons for the occurring motor overload and preliminary spindle stall.
- Examine the influence of weld parameters on the joint quality
- Examine the influence of the material by comparing Mo and TZM.

The up-scaling of the process requires information about the power and energy demand during the RFW process. In IFW, the energy *E* that is converted into heat in the friction surface originates from the inertia moment *J* of the flywheel, and can be calculated according to:

$$E(t) = \frac{1}{2} \cdot J \cdot \omega(t)^2 \tag{1}$$

Scaling of IFW processes is done using the specific weld energy and keep it constant [13]:

$$\frac{E}{A} = const. \tag{2}$$

In DDFW, the weld energy, can be calculated from the product of motor load, weld speed, and time [1]. The specific weld energy and weld parameters of the laboratory scale experiments were used to propose a DDFW process for Mo-tubes of 5000 $mm^2$ cross-section.

## 2. Experiments

The investigated materials were commercially pure Mo ( > 99.97 wt%) and TZM (0.5% Ti, 0.08% Zr, 0.01–0.04% C, all wt%). The production route of the material was sintering, hot forging, stress-relieve annealing, and machining.

Welding experiments with medium-size Mo tubes of 4400 $mm^2$ cross section with an outer diameter (OD) of 150 mm, and an inner diameter (ID) of 130 mm were performed. The welding machine was a heavy-duty DDFW machine with 150 kW drive power and 1250 kN maximum forge force. Axial force, speed, upset, and motor load parameters were recorded. Investigated parameters were friction pressure, welding speed, and friction time. The Mo tubes were pre-heated in a furnace to 400 °C.

In order to investigate the material behavior during the process a friction stir welding machine (MTS I-STIR BR4) was adapted for rotary friction welding (RFW). The machine capabilities were a maximum axial force of 35.6 kN, spindle speed 3200 $min^{-1}$, 180 Nm torque, and axial travel of 15 mm. Small-size friction welds with Ø12 mm rods of Mo and Ø9 mm rods of TZM material were conducted. To exceed the ductile-brittle transition temperature, an in-situ pre-heating phase was employed [14]. Friction at low pressures (< 10 MPa) resulted in a constant temperature of 350 °C in 8 mm distance from the weld interface without significant plastic deformation. The welding process started by increasing the pressure from pre-heating to friction pressure. Fig. 1 shows the input parameters pressure and speed for Mo and TZM. It should be noted that TZM requires a higher friction and forge pressure than Mo to produce successful welds due to the higher strength. Varied welding parameters were friction pressure, welding speed, and forge condition to determine optimal welding conditions. The forge condition is determined by three parameters:

1. Forge point: the initiation of the forge phase in relation to the current spindle speed. In the small-size experiments the forge force was applied upon deceleration start. This is common practice in friction welding and referred to as “forging into the turning spindle” [3].
2. Forge force gradient: the rate of force increase from friction force to forge force.
3. Spindle deceleration: the deceleration rate from welding speed to spindle stop.

In order to derive information about the upscaling to larger cross-sections, the specific energy was calculated from the motor load and weld speed. The in-situ pre-heating phase was not included in this calculation, since the heat dissipation reached an equilibrium with the inserted power by friction and caused no significant sample deformation. The calculated values therefore represent the energy input during the friction and forging phase.

The welded samples were inspected visually to evaluate the flash shape, the geometric symmetry of the weld and the visual appearance. Metallographic investigations were carried out on welded samples using light optical microscopy to investigate the quality and the microstructure of the welds.

## 3. Results & discussion

### 3.1. Molybdenum medium-size format

Welding experiments with different parameters (weld speed, friction pressure) were conducted; however, regardless of the welding parameters, the experiments showed a preliminary spindle stop due to insufficient motor power. The results have been published previously [12] and are summarized below showing the welding parameters of one representative weld in Fig. 2. The spindle speed decreases immediately when the friction phase starts. The exponential increase of the upset during the friction phase with an upset rate up to 7 mm/s should be mentioned. Fig. 3 shows an image of the friction welded Mo-tube. Although the weld flash indicates a good weld, defects were found in metallographic cross-sections.

### 3.2. Molybdenum and TZM small-size formats

The laboratory scale experiments enabled the variation and measurement of the welding parameters: friction pressure, welding speed, and forge condition. Fig. 4 shows the influence of the specific power on the upset behavior of Ø12 mm Mo rods for three different weld speeds. The specific weld power, and consequently the specific weld energy, decreases with decreasing weld speed. As a result, the upset decreases from 5.2 mm at 100% weld speed to 3.9 mm and 2.7 mm for 95% and 91% weld speed, respectively.

The specific weld power curves of Mo in Fig. 4a show two separate peaks that are the result of the friction torque during the RFW process. The first peak can be attributed to the friction phase and results from the interlocking and breaking of asperities and subsequent softening of the material by frictional heating. The second peak is the result of the forge phase where the torque rises with increasing forge force, and sharply falls off to zero with decreasing weld speed. No steady-state could be observed between these two peaks that would result from the balance between material softening and strain hardening [2].

Fig. 5 shows the upset as a function of the specific weld energy of all performed Mo welds. Insufficient bonding can be observed if the specific energy is low and the resulting upset is < 4 mm. It is assumed that < 4 mm upset the impurities are not completely expelled into the flash and, therefore, the joint quality is poor. If the welding energy is increased above 120%, excessive plastic deformation leads to an instable process with high upset rates and upsets > 12 mm. Between 4 mm and 12 mm upset, sound welds were produced and the image insert in Fig. 5 shows an example. The solid line represents process conditions with maximum spindle deceleration and low forge force gradient. If the forge force gradient is increased, the upset increases at