HIGH SPEED FRICTION STIR WELDING OF THICK COPPER PLATES

Max Hossfeld

Rapid Technic AG, Industriestrasse 7, Killwangen,
Switzerland; e-mail: fsw@rapid.ch

ABSTRACT

When welding large copper parts, the process is strongly limited by the high thermal conductivity and capacity as well as the high temperature strength of copper. These slow down the welding process and require a large heat input. By this the process forces are high and probe failure is a severe issue. Typical welding speeds of thick copper plates today are around 50 to 150 mm/min under laboratory like conditions, requiring a spindle torque up to 1000 Nm, excluding usual multipurpose FSW-machines from this application.

This study shows the process and tool development including the verification of a robust tool design. The process is carried out on a multipurpose machine reaching welding speeds up to 500 mm/min in 20 mm rolled Cu-OF.

A significant reduction of the process forces, especially traverse force and spindle moment is reached. Due to the relatively low heat input good mechanical properties could be achieved. Tool design, parameters, microstructure, hardness profiles and tensile properties are shown.

KEYWORDS

friction stir welding, copper, thick sheets, high speed, tool development

INTRODUCTION

For a customer in the process manufacturing branch a big meander shaped unit consisting of thick copper sheets plus connectors had to be designed and welded. In essence, the unit is a cooling coil like pipeline for an aggressive and very hot chemical that is cooled down with the aid of a liquid circulating around the outside of the unit.

With dimensions up to approximately 9 m x 2 m x 0.5 m and a sheet thickness ranging between 20 to 35 mm the whole weldment weights several tons.

Due to the chemical flowing inside, the pipe is exposed to a severe corrosive and abrasive environment. In addition, the unit is stressed by temperature cycling and has to act as a structural component to some extend as well.

Different copper alloys and joint geometries were tested for this application. This paper provides an insight into the process development and shows the welding results for the welding of 20 mm oxygen free copper, Cu-OF / EN-CW008A.

REQUIREMENTS AND CHALLENGES

Based on the application we faced some requirements and challenges for the development of the process and its implementation:

- Cooling liquid and chemical must not get in contact at all circumstances
- Absolutely no voids or inclusions were allowed in the weld
- No formation of a predefined crack path by weld imperfections as joint line remnants (oxides) etc. allowed
- Metallurgical notches had to be avoided, e.g. a hardness of at least 60 HBW had to be reached within the weld while a ductile behavior of the unit is essential to detect deformations before a possible failure
- Pin failure would irreparably damage the unit
- Only a very low distortion was allowed

FURTHERMORE ADDITIONAL ISSUES AROSE FROM PRELIMINARY TESTS:

- Because of the long weld length and the heat input required, the high thermal conductivity and the capacity of copper the whole component gets and stays hot for a long time. For this reason, the handling of the component as well as keeping the heat input as low as possible is an important issue
- High welding forces and the thermal expansion of the parts require an extensive but adjusted fixing and a strict monitoring of the part's tolerances
- Not more than 35 mm shoulder diameter was possible because of the joint geometry and position on the original and the risk of a deformation of unit

Because of the unit's dimension and geometry the welding had to be carried out on a machine with a big machining table. Furthermore, the quantity ordered and the delivery time did not permit a special purpose FSW machine. Therefore, all welding was done on a MTI GG-1 at Rapid Technic Switzerland, Fig. 1. The GG-1 at Rapid is a multi-purpose FSW machine capable of a process force of 67 kN and equipped with a 16 kW spindle with 186 Nm maximum torque. This is little compared for instance to the special purpose machines used by Andrews or Cederqvist [1, 2]. For example, the FSW machine used for welding 50 mm copper in Laxå, Sweden is capable of more than 50 kW and 1300 Nm at low spindle speeds [2].

Fig. 1. MTI GG-1 multipurpose FSW machine and final tool design made from Nimonic® 105

PROCESS AND TOOL DEVELOPMENT

Mainly because the lack of spindle torque we faced some serious issues with overloads leading to a special tool development. Requirements were as followed:

- Because a minimum heat / power input is required for welding and the available torque is comparatively little especially at lower rpm, the spindle speed had to be significantly higher than the typical 350 – 500 rpm [1, 2].
- The objective of a low energy input per unit length as well as a low absolute energy input required a fast welding process, causing a high traverse reaction force

Based on that and the process requirements described, the main focus was on the design of the pin. First, we had to lower the reaction force to enable higher traverse speeds. We did this by reducing the projected area of the pin as well as choosing a design with an active material transport from the front to the back. Second, we increased the convective heat transfer from the top to the bottom of the weld as well as the heat generated by the pin itself inside the weld. We did this by increasing the swept material volume per revolution and transferred some functions of the shoulder to the pin. By this we were able to increase the pin diameter and could use a kind of shear thinning effect. Third, to withstand the still quite high traverse / shearing force, we built up a robust pin design with continuous strong middle section and a very smooth transition between pin and shoulder with a small notch effect. Because the shoulder diameter was limited by the use case and the spindle torque available, we used a scrolled shoulder for adjusting its heat input and for balancing the heat input between shoulder and pin. Because of the expenditures for tools and testing a numerical tool developed earlier was used to support the tool development [3].

The final design is shown in Fig. 1. The tool is made from the nickel-based high-temperature low creep superalloy Nimonic® 105. We chose the material because of its good resistance to elevated temperatures and because it removes only little heat from the process zone due to its relative low thermal conductivity of approximately 25 W/(m · K), what lowers the spindle power needed significantly. The shown design is able to weld the use case from 700 rpm / 250 mm/min up to 1100 rpm / 500 mm/min while keeping the torque and the traverse force constantly low. However, the process envelope becomes smaller at higher traverse speeds. Welding and results

The welding results shown were produced with a spindle speed of 850 rpm and a traverse speed of 350 mm/min. The plunging speed of the tool was set to 40 mm/min, rendering a subsequent dwelling time unnecessary. For compensating the machine's deflection during welding we used a theoretical preset tilting angle of 4.5° and a heel plunge depth of 1.5 mm. By this a stable compression of the weld on the backside of the shoulder was possible, merging the flow regimes of shoulder and pin effectively and without imperfections. Furthermore, through this approach the average contact pressure could be kept as low as 32 MPa resulting in a steady state forging force of 44 kN, a traverse force of 12.5 kN.

The cross section of the weld and the resulting microstructure are shown in Fig. 2. Due to the dynamic recrystallization during FSW, the stir zone shows the typical fine and equiaxed grain microstructure (detail D2), while in contrast the base material is dominated by elongated grains and twin grain boundaries. Because of the locally limited and quite fast welding process no significant alteration of the microstructure of the base material could be found as close as 10 mm to the thermo-mechanical affected zone (TMAZ), detail D1. This result was supported by the measurement of hardness.

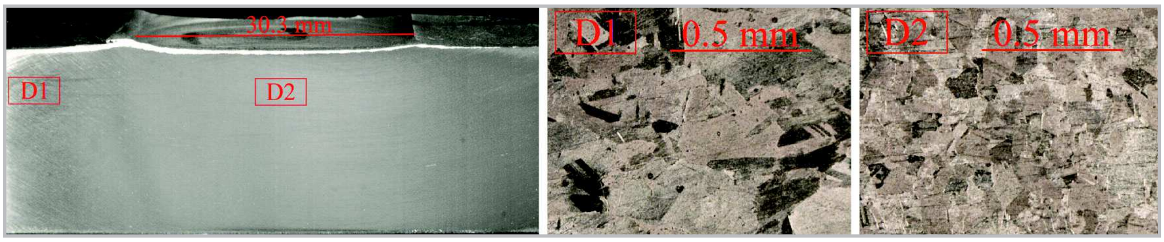

Fig. 2. Cross-section polish of the weld and etchings of base material and stir zone (5%-HNO3, 30 Sec)

The hardness profiles over the cross-section are shown in Fig. 3. They were measured in the middle of specimen (red) as well as 2 mm from top (blue) and bottom (green). The profiles reveal a typical U-shaped hardness drop to 60 HBW within the joining zone. This was already satisfactory regarding the described requirements. During this work it became apparent that the hardness drop was not only strongly linked to the weld pitch but also to the weld duration respectively the traverse speed. For example a smaller hardness drop to about 70 HBW could be reached by using a 1050 rpm / 450 mm/min parameter set.

The hardness drop in the joining zone is directly linked to the component behavior. Because a ductile behavior of unit and weld was demanded, tensile tests with an optical deformation analysis (ARAMIS system) were carried out. The specimens were tested with an as welded surface; the width was 25 mm, the measuring length 60 mm, the clamping length 100 mm. The result of the tensile test of the 850 rpm / 350 mm/min parameter set is shown in Fig. 4. A good ductile behavior of the weld is reached, as expected from the hardness profile and because of the slightly smaller thickness strains localize within the weld first. Nevertheless, the ductility and the tensile strength of the base material are almost reached by the joint; in addition the yield strength of the base material is reached.

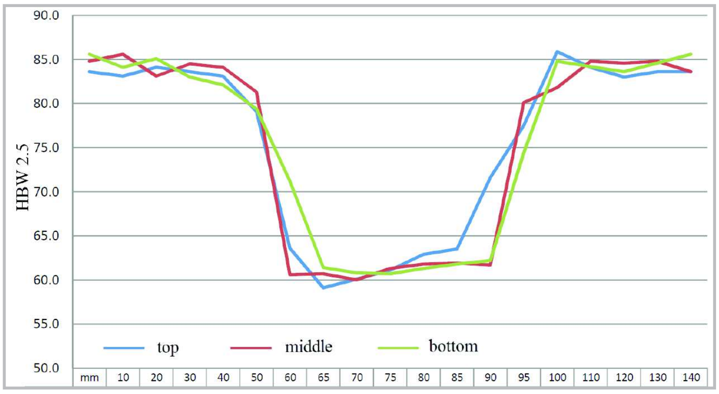

Fig. 3. Hardness over the cross-section of the weld, Brinell scale, 850 rpm / 350 mm/min

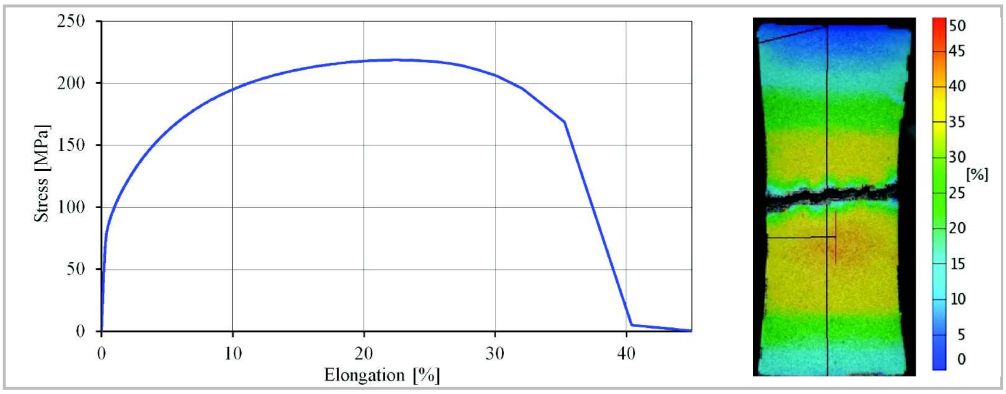

Fig. 4. Tensile test curve of FSW joint (transversely to the weld) and local axial strain distribution on the backside of the specimen at failure, 850 rpm / 350 mm/min

CONCLUSIONS

For a special application the deep welding of big copper parts had to be enabled on a multi-purpose FSW machine. In addition, because of different issues and requirements like handling a fast welding process with a low energy input per unit length was desirable. Since the spindle torque of multi-purpose machines is typically low compared to the requirements of welding thick copper plates especially at lower rpm a different approach was needed to provide a sufficient heat input as well as increasing the traverse speed. We did this by using significant higher rpm than usual combined with an improved and adjusted tool design that help keeping the joining process more local. By this the heat input and so the torque required as well as the process' reaction forces could be reduced so that welding the part on a MTI GG-1 was possible. The developed tool is able to weld 20 mm copper plates over a quite large and to the greatest possible extent stable process envelope. For these welding depths unusual high weld pitches are reached. The mechanical properties reached are close to those of the base material. As shown, the customer requirements could be met.

REFERENCES

1. Friction stir welding - an alternative method for sealing nuclear waste storage canisters, R.E. Andrews, TWI Ltd, Cambridge, United Kingdom, 2004.
2. Friction Stir Welding of Copper Canisters Using Power and Temperature Control, L. Cederqvist, PhD thesis, Lund University, Sweden, 2011
3. A new approach to modelling friction stir welding using the CEL method, M. Hossfeld, E. Roos, Advanced Manufacturing Engineering and Technologies, Stockholm, Sweden, 2013.