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Deterioration of EUROFER plates by severe bending

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Abstract

Many components of the blanket box for a future fusion power plant are fabricated of curved EUROFER plates with cooling channels. The bending process causes an investigation of the expected material deterioration. The present paper focuses on the deterioration results caused by a cold bending process of a solid tin as a first approach to such a technology. Two possible countermeasures against this deterioration have been taken and checked as an important request of this paper. The results are showing the feasibility of a bent procedure for a U shaped cooling plate of a breeder unit.

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1. Introduction

A future fusion reactor will need a heat exchanger system and a wall protection component, called blanket box (BB) [1,2]. This box will accommodate the breeder units (BU) which will cool and contain the breeder material.

Radiation will cause thermo-mechanical stress and an embrittlement of the material. Therefore the current paper should investigate as most wanted property fracture toughness. There is firstly the question of 'expected' proof of changed fracture toughness properties by bending as a possible structural weakening. The determination of fracture toughness is sufficient for the manufacturing technology attempt caused by application.

The current status of discussion [3–6] predicts a radiation caused shift in ductile to brittles transition temperature (DBTT) between 30 °C and 50 °C (17 dpa, 400–450 °C). Normally the used EUROFER shows a DBTT between −100 °C and −80 °C. If a step of the manufacturing process of a BB or BU generates regions with a material deterioration, the DBTT could shift for instance to −40 °C. The radiation could generate an additional shift in the DBTT in the range of 50 °C to first order yielding a DBTT of 10 °C possibly. The combined effect should be investigated, if the current investigation will yield results like changed fracture toughness properties by bending. Such an increased DBTT in a deteriorated region of the work pieces will not be a problem during working reactor caused by an operating temperature in the range of 500 °C. But a lowered upper shelf energy (USE) would

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reduce the safety function of the BB against plasma impacts. After life time the BB has to be removed outside at room temperature. Then there will be a risk of brittle fracture of the BB and of the BU. It has to be handled very carefully or the life time has to be decreased.

Now the question of necessity of bent cooling plates has to be discussed. The heat has to be removed by a flow of helium (80 bar, 500 °C) through cooling channels inside nearly all components of the BB and BU. The necessary efficiency can be reached by curved plates with cooling channels according to the current status of discussion [2]. An additional advantage of curved cooling plates consists in avoiding welds. But the use of a filler metal necessitates a cold bending process which damages the material in the bent region. This can generate the former mentioned DBTT shift. A famous application of a bent cooling plate is the first wall plate (FW). A further promising application is a U shaped cooling plate with an inserted middle plate as a BU part [2,7]. The lower ratio of bending radius and of plate thickness of the U plate in contrast to that of a FW causes to choose the U plate as subject of the current paper. This will increase the material deterioration and will yield clear results of the countermeasures.

2. The U plate manufacturing procedure

Fig. 1 gives an overview of the assumed manufacturing sequence. Two symmetric work pieces are produced by milling parallel grooves for the later cooling channels. 'O' represents a coolant outlet with a manifold. The weld area is prepared for a diffusion weld process like hot isostatic pressing (HIP) [8] or a uniaxial diffusion weld procedure (U-DW) [9]. B: The half pieces are connected by a diffusion weld process and unnecessary material has been cut away. Typical lateral dimensions of this plate are $97 \times 20\ \mathrm{cm}^2$ with a thickness of 5 mm. C: The plate has been bent twice to a U, later called U plate. D: The middle plate (coolant inlet 'I') has been produced like described in A and B. Wholes are drilled or milled in the U plate in order to let in the coolant escaped from the middle plate. The middle plate is inserted. The junction between U plate and middle plate needs a TIG weld process [7] performed by a special setup. The space between these plates has to be increased as large as possible by a small bending radius which enables the future use of such a setup. E: The assembly has been weld to the 'back plate' which contains the supply pipes for the coolant. Note only one U plate is displayed, a BU with two U plates is under discussion [1,7]. The thin lines represent the canisters for breeder material and the beryllium pebble bed. Such a BU can be inserted in a future blanket module in a fusion power station.

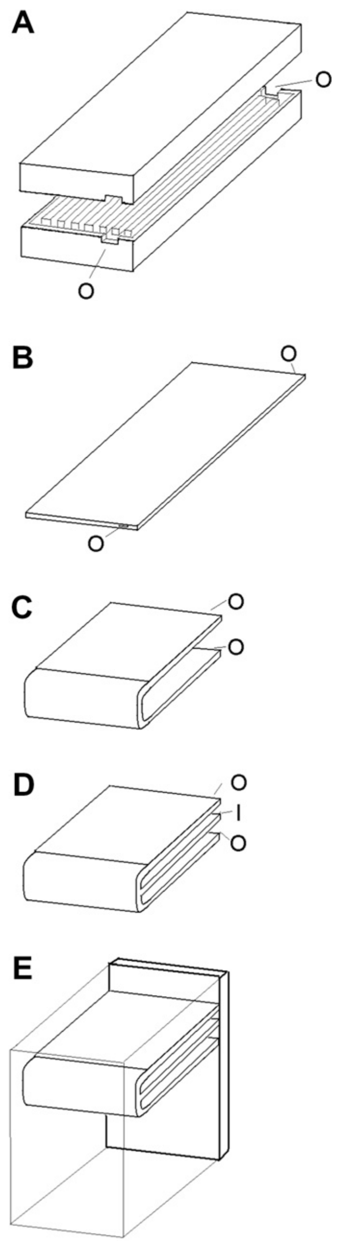

Fig. 1. Scheme of a BU manufacturing sequence basing to a U-shaped CP.

The most critical component will be the bent cooling plate of the BU according to the current discussion. It has now to be investigated whether a cold bending process will embrittle the material of such a component, see step C in Fig. 1. The cold bending process is caused by the need for a filler metal. It is well known that such a cold worked material can show an improvement of tensile parameters and decreased fracture toughness properties.

A second important question will be whether a heat treatment can lower this damage. Such a material damage can be detected sensitively by a Charpy impact test.

3. Sample production

The production of a complete cooling plate (CP) will be very expensive. It cannot yield the correct results. The cooling channels [1,2] in an approximately 4.5 mm thick U plate inhibit a correct Charpy impact specimen production taken parallel to the surface from such a plate caused by the in contrast to the plate thickness huge dimensions of $3 \times 4 \times 27\ mm^3$ of such specimens, see also Fig. 2. The specimens would contain the wholes of the cooling channels. Charpy impact specimens taken perpendicular to the U plate surface would own the disadvantage of being too small. The ribs between the cooling channels are only about 2 mm thick. These dimensions cause the use of equivalent 4.5 mm thick tins of EUROFER taken from batch 63997. The tins – 5 cm to 20 cm lateral dimension – will be bent with an inner radius of 6 mm. The radius has been chosen compromising design requirements, former mentioned manufacturing requirements and rules according to a table of bending radii for high strength steel [7,10]. The rules are indicating a permitted minimum radius of 8 mm. It has to be mentioned that the bending radius of a first wall plate will not be as critical as in the case of the here discussed U plate. Consequently each tin will possess three 90° arcs with an accuracy of less than 2°. Each 'bending zone' of a tin arc can be separated into four Charpy impact specimens: This limits the number of specimens. The specimens have been marked according to the original tin, arc and, most important, the position inside the arc: This allows the determination of differences between samples from the centre position and margin position of the arc, as shown in Fig. 2. The Charpy impact specimens are subjected to different heat treatments. The specimens of the first tin are not exposed to any heat treatment. This tin is later called tin A. These specimens demonstrate the possible material deterioration after bending. The normalisation procedure of the chromium steel EUROFER is well known [11,12]. It yields the parameter of the suggestive heat treatments: The second tin B is exposed to a complete normalisation consisting of two steps, here performed by 980 °C for half an hour and 730 °C for three hours. The 980 °C heat treatment step is undesirable for some applications, for instance in the case of a beryllium containment. Consequently, specimens of the third tin C will show countermeasures of a heat treatment at 730 °C for three hours only. All Charpy impact specimens have been tested in a notched bar impact testing machine.

4. Results and discussion

The experimental results of this paper are displayed in Fig. 3. The symbols represent the impact

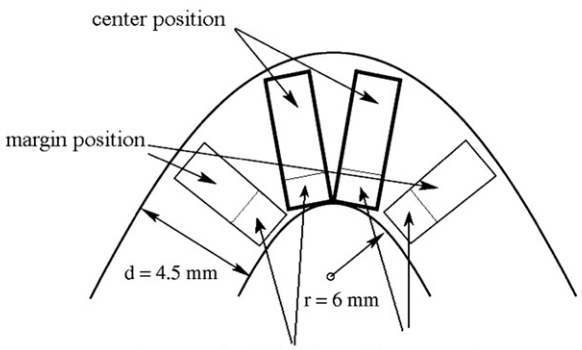

Fig. 2. Cross-sectional sketch of different specimen positions.

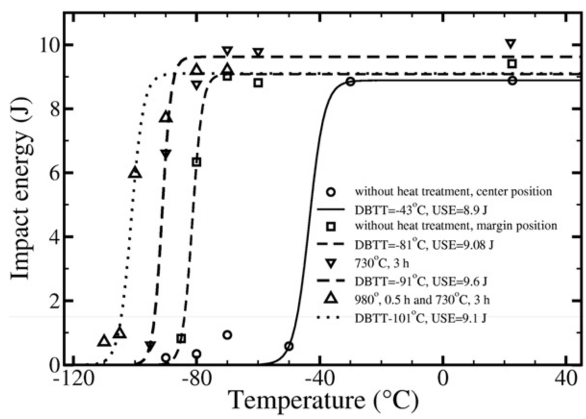

Fig. 3. Results of Charpy impact testing, the different specimen positions are displayed in Fig. 2.

energy measured versus specimen temperature. All lines are based on an empirical model of the non damaged material behaviour of EUROFER. They refer to the DBTT, the upper self energy (USE), and the slope of the curve at the DBTT [9]. An increase of the DBTT or a decreased USE is interpreted clearly as deterioration of the material. EUROFER without a material deterioration has a USE of approximately 9.0 J and a DBTT of −100 °C.

One most interesting result was obtained with the specimens of tin A (without any heat treatment after bending), as displayed by circles and squares. The specimens show a huge increase of the DBTT. The specimens exhibit a critical increase of about 60 °C (full line in Fig. 3) of the DBTT which are taken from the centre position of the arc. This effect cannot be neglected as told by the introduction! It has to be mentioned that neutron radiation may possibly increase the DBTT again! Specimens taken from the margin position show that the material deterioration in this position is far less than at the centre position, as obvious from the smaller increase of the DBTT, see the dashed line of Fig. 3.

The results obtained with tin C (only one-step heat treatment at 730 °C) shall now be discussed for a better understanding. It was surprising that no difference in material deterioration could be observed between specimens taken from the centre or margin positions. The difference in the impact energy was less than 0.4 J for specimens taken from centre and margin positions and tested at the same temperature. Hence, only the mean values are represented by the ‘down’ oriented triangular symbols of Fig. 3. The dash-dotted line indicates an increase of 10 °C of the DBTT only and a less increased USE caused possibly by a hardening process. That might be neglected. But unfortunately, the symbols represent a deviation of the ideal material property curve of the used EUROFER. This additionally indicates a small damage of material. This is why tin B is exposed to a complete normalisation procedure. The specimens of this tin (top-orientated triangular symbols in Fig. 3) prove that the bending induced material deterioration can be healed by such a procedure. An increase of the DBTT and a decrease of the USE cannot be determined by Charpy impact specimens taken from tin B. A deviation of the experimental impact energy values from the ideal curve is observed for the temperature range from −100 °C to −80 °C as well for the specimens of tin C. This small and negligible material deterioration cannot be removed.

A dramatic change of the USE did not have been observed in any specimen serial of all tins.

It has to be noted that due to the lack of material, additional necessary tensile tests could not be performed. It is now the question whether such a material damage can change tensile material properties or not.

5. Conclusion

The results of this investigation demonstrate that a cold bending process of EUROFER causes a non-negligible material deterioration for the U plate. The material deterioration will not influence the USE. The material damage shown by change of DBTT can be removed by a fitting and well-known normalisation. An additional heat treatment procedure during the future manufacturing process of BB or BU according to the ongoing design revision has to be considered and discussed. A future radiation program should contain Charpy impact samples taken from bent tins as told by this paper. There are a lot of curved plates in the BB, and the question of additional DBTT shift has to be clarified. Furthermore, it has to be tested whether a frequent normalisation of EUROFER will yield the same material parameters or not.

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