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Optimization of the EUROFER uniaxial diffusion weld

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Abstract

This paper presents our investigations of the two step uniaxial diffusion weld process for the EUROFER 97 chromium steel. Such a process optimization has to balance weld quality, change of tensile properties and compressive deformation of the future work piece. This process will be used for the manufacturing of any cooling plate production for a breeding blanket component of a future power plant.

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1. Introduction

A central component of a future fusion power plant [1] will be the breeding blanket (BB) with its breeder units (BU) [2]. The large amount of energy deposited into such an assembly requires all parts to be cooled with an efficient high performance coolant system to avoid overheating. That kind of system can be built completely from plates with curved cooling channels inside. The most promising manufacturing process is the production of symmetric half plates with cooling channels made from milled in grooves and to connect these half plates by a diffusion weld (DW) process. The advantages of this manufacturing process are perfect junctions between the half plates and the possibility to produce cooling channel systems of any shape. The DW process has to be performed at a high temperature with appropriate pressure and time applied. This requires an optimization of the DW parameters. Former investigations point out the advantage of a two step diffusion weld process where different sets of parameters are used in each step [3]. Three issues have to be investigated for a optimized process variant: First, the quality of the welds must be investigated by tensile and Charpy impact experiments. The second issue is the consequence of the heat treatment during the DW process. It may change material mechanical properties. Such a change can be detected by similar tests with specimens taken from sample regions without weld, yielding so called base material properties. Third, the compressive deformation of the work piece has to be considered.

2. Experimental

2.1. Sample production

All samples discussed here are produced in the same manner. Small cubes with typical dimensions

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of 25 mm × 30 mm for the future weld surface and a thickness of approximately 20 mm are sawn out of 25 mm rolled plate material of EUROFER 97 batch 83697. The weld surface is then conditioned by a high speed dry milling process. Former DW experiments with wet milled weld surfaces have not been as successful as DW experiments with a dry milled surface [4]. A 'new' high speed dry milling process has been developed for the current process for small roughness and good reproducibility. The surface roughness obtained is typically characterized by a R_a value of between 0.1 and 0.5 μm and a R_z value between 2 and 3 μm. R_a represents the typical amount of neighbouring hills 'elevation' difference, while R_z stands for the long range surface roughness as representative of the height difference between 'valley' and 'mountain'. R_z and the width of the 'valley' (13 μm) are the dominant surface topology properties for the void model used of the DW process [5]. Each of the cuboids is cleaned four times for 10 min in an ultrasonic acetone (38 °C) bath. Two of these cuboids are then placed as DW specimen in a universal tensile test machine with a vacuum furnace. The vacuum pressure is better than 10^{-5} mbar to avoid unwanted chemical reactions (mainly oxidation) of the EUROFER steel. This furnace can warm up the samples (maximum diameter 100 mm) to a temperature of 1600 °C with a rate of 20 K/min. The tensile test assembly can apply a uniaxial bonding force up to 50 kN. This method of generating the bonding force gives the name for the DW variant: U-DW – 'uniaxial diffusion weld' – process. The advantages are very well controlled experimental conditions of the weld process. For instance the bonding force can be measured by a high accuracy load cell and the DW specimen temperature by a directly welded thermocouple. This setup can also measure the compressive deformation (CD) of the work piece during the diffusion weld process. This is an additional mighty tool of process development. Otherwise the knowledge of the compressive deformation can be used to hold the weld pressure constant to first order in case of a huge compression of the U-DW sample. The post weld heat treatment (PWHT) applied to all samples in this furnace was 980 °C 30 min and 730 °C 3 h. The cooling rate for the temperature range between 800 °C and 500 °C lays at approx. 6.8 K/min to avoid ferritic separations [6].

2.2. U-DW processes

This paper contains results from two kinds of U-DW variants: The first is the 'one-step' U-DW process where temperature (1010 °C) has been held constant. The process time and pressure have been varied. The temperature has been chosen by theoretical estimations of the U-DW process [5]. The second variant and the main goal of this investigation is the development of a 'two-step' U-DW process. The current state of knowledge separates the driving forces of the DW process into plastic deformation, different diffusion processes parallel and perpendicular to the joining surface and visco-plastic creep. These driving forces are more or less temperature and pressure dependent. The basic idea of the optimization of the 'two-step' U-DW process consists in the determination of weld parameters which selectively prefer one or the other driving force. The first process step should flatten the weld surface with high pressure to generate a perfect mechanical contact between the two half pieces. The necessary bonding pressure for this step is given to first order by the yield strength. The comparison between future BB dimensions [2] and industrial setups causes a desirable weld pressure of no more than 30 MPa which corresponds to a first step weld temperature of 1010 °C. The second step of the process should improve the weld and heal defects in the crystal lattice. This consideration requires application of a higher bonding pressure and a lower temperature during the first step of the 'two-step' U-DW process, while the temperature should be increased during the second step to accelerate diffu-

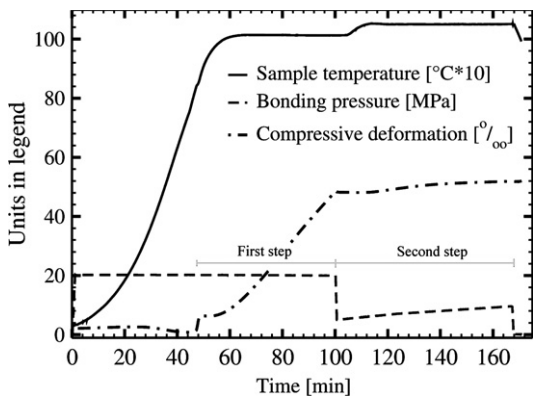

Fig. 1. Time dependent measured diffusion weld parameter during a two step U-DW process. Note the negative CD is displayed.

Table 1
U-DW samples: this table gives a short overview of the discussed U-DW samples

Number	First step pressure (MPa), time (min)	Second step pressure (MPa), time (min)	USE (J)	DBTT (°C)	Compressive deformation (%)
1	20, 23		8.7	−38	3.7
2	20, 40		6.9	−67	5.8
3	20, 150		9.2	−98	4.5
4	10, 120		7	−40	1.0
5	15, 150		7.2	−103	7.4
6	20, 40	10, 33	8.4	−67	6.1
7	20, 40	5–10, 66	8.4	−83	6.5
8	20, 40	7.5, 66	7.8	−87	6.1
9	18, 123				8.6

Note the sample numbering is quite different in other publications of the authors caused by better understanding. Warming up last 1 h and is not included. All samples are welded using a temperature of 1010 °C during the first step and 1050 °C for the second step.

sion processes. Decreasing of the bonding pressure during the second step avoids a huge sample CD. This is illustrated in Fig. 1. The sample has been compressed during the first step. By changing the process parameters the CD has been stopped. The temperature of 1050 °C has been determined with the recrystallization temperature of approx. 1078 °C [6] in mind. Now it has to be investigated whether the weld quality has improved or not.

Table 1 gives an overview of weld parameters and mechanical properties for the U-DW specimens. It has to be noted that a DW process investigation is much cost and labour intensive. Production of one U-DW sample including PWHT requires three days of processing. Each U-DW sample is then machined by spark erosion into five tensile and ten Charpy impact specimens (KLST, 3 mm × 4 mm × 27 mm, with a notch) to investigate the welds. Base material properties need additional five tensile and Charpy impact specimens. This paper treats eight U-DW samples corresponding to more than 160 mechanical test specimens.

2.3. Results of tensile tests

All U-DW welds have been investigated by tensile test specimens at room temperature, 300 °C, 500 °C and 700 °C. These values have been chosen according to the future operating temperature of 500 °C, other values will be used in the future for interpolations of tensile strength of local hot spots. Additional samples have been taken from other regions of the U-DW samples for the determination of base material tensile properties. It was surprising that tensile properties of samples with welds and those samples without welds have been the same. The deviations of yield strength and rupture strength have been less than 5% for these two groups of samples. Fig. 2 shows the averaged results represented by the solid line. The error bars display the amount of maximum deviation from the mean value. The literature [3,7] shows that nearly every DW process yields good tensile results. Therefore, this kind of investigation is not a very sensitive instrument for the determination of the weld quality. But a comparison of tensile properties between our results and EUROFER 97 taken from [6] shows a decreased yield and rupture strength and an increased failure tensile strain. Unfortunately, the samples for [6,8] have been taken from a different EUROFER batch 83698 with a different heat treatment ([6]: 980 °C, 30 min, 750 °, 2 h, circles in Fig. 2; [8] 980 °C, 30 min, 760 °C, 2 h, squares in Fig. 2). So an additional investigation of tensile

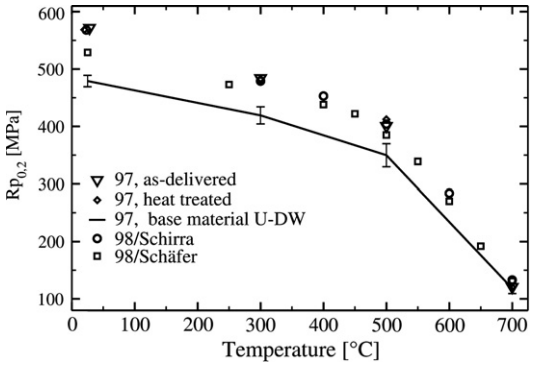

Fig. 2. Tensile properties of U-DW welds and base material with different heat treatments: 97: Batch 83697, 98: Batch 83698, 'Schirra' stands for [6], 'Schäfer': [8] and tensile results of for as-delivered material agree with the heat treated results for as delivered material.

properties has been started. Tensile samples have been cut from the material 'as-delivered' (large triangle in Fig. 2) and after a single PWHT (small diamonds in Fig. 2). The tensile results of the 'as-delivered' specimens do not differ from those samples to which a single PWHT has been applied. Fig. 2 shows the results of these two sample groups with diamonds and triangles. These results agree completely with the results of [6,8]. The difference of tensile properties between U-DW samples and the 'as-delivered' material cannot be a result of the different heat treatment [8]. This proves that the heat treatment of the U-DW generates an additional change of tensile properties. This change is irreversible by this PWHT. It has to be mentioned that similar results of room temperature yield and rupture strength of DW (approx. 1050 °C 120 min) specimens have been published by [3]. The tensile properties change can be caused by grain coarsening [9] which has to be investigated in the future.

2.4. Results of Charpy impact specimens

The bulk material and of course the welds will embrittle by neutron radiation. This makes it necessary to determine the ductile to brittle transition temperature (DBTT) which will be increased during the lifetime of the BB. A collapsing magnet field or other accidents can generate a high mechanical impact of the plasma into the BB. The protection of the vacuum vessel against the collapsing plasma is an important function of the BB. The fracture toughness or the upper shelf energy (USE) has to be determined too. The values of USE and DBTT of the weld should be kept close to the base material properties of about 8.9–9.1 J and −95 °C, respectively. Other values could decrease the lifetime and the safety function of the assembly.

2.4.1. 'One-step' process

The first sets of U-DW samples – 1–5 see Table 1 – were used in an investigation of process time, while applying a constant pressure of 20 MPa. It is easy to see by the small USE that a weld time less than 40 min will be not sufficient. An increase of weld time to 150 min yields an adequate DBTT. But the CD value of only 4.5% for sample 3 needs some discussion. Sample 9 which had been welded with lower pressure of 18 MPa and shorter time of 123 min shows nearly double CD value of 8.6%. An additionally developed compression creep model predicts about 13% CD for sample 3, while the compression behaviour of all other U-DW samples is predicted well. The determined USE is a little bit increased in comparison to the base material value. This suggests a hardening in the sample 3, it has been taken as first sample nearly from the edge of the plate where this might be the reason of this phenomenon. Therefore, this CD value has to be marked as not typical.

The next technological question is determination of the minimum bonding pressure with respect to large area work pieces. The answer is given by samples 4 and 5. A bonding pressure of 15 MPa is not sufficient at a temperature of 1010 °C for the first step, proven by a reduced USE of the welds. Therefore a pressure between 15 and 20 MPa must be the desired value. A previous model had estimated that the minimum bonding pressure should be in the order of 10 MPa [7] using a two times higher R_a as roughness. The fracture surface of sample 4 explains the discrepancy. It shows grooves from the high speed dry milling process discussed in chapter 1. It has to be suggested that the long range surface roughness causes the minimum bonding pressure.

2.4.2. 'Two-step' process

Development of the 'two-step' U-DW process has therefore to start with the weld parameters of sample 2 (first step: 20 MPa, 1010 °C, 40 min). Pre- investigations and the compression creep model [9] gave the result of a maximum bonding pressure of 10 MPa and a temperature of 1050 °C for the second step. Fig. 3 shows the results. The dotted line shows the Charpy impact test result of sample 2. It is clearly shown by the decreased DBTT that every

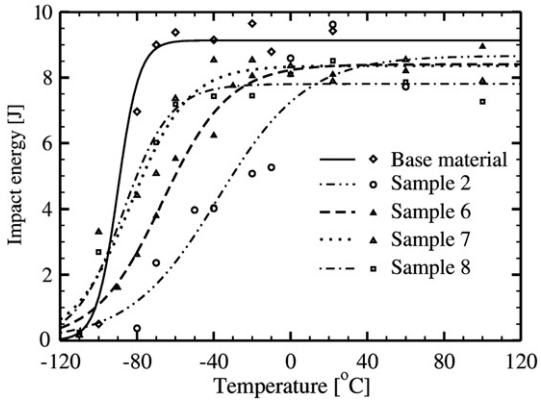

Fig. 3. Results of Charpy impact testing of different U-DW samples.

variant of the two step U-DW increases the weld quality. Sample 6 shows an increased USE of 8.4 but not a better DBTT. This causes to prolong the time of the second step from 33 to 66 min. The possibly increased CD is not a problem for the discussed variant of the U-DW process due to a vanishing compressive deformation rate during the second step (see Fig. 1). The next attempt uses a time ramp for the bonding pressure. The weld will reach the same USE but with a decreased successful DBTT of about −83 °C. These results set the parameters of the last sample 8–66 min bonding time and 7.5 MPa bonding pressure for the second step, according to the former discussed sample 7 that averaged 7.5 MPa. The DBTT of specimen eight has been decreased a little bit, but this might be within the experimental variation. The USE is decreased which agrees with the model results [7,10]. Regarding the lower number of U-DW samples the USE depends on the pressure of the second step for a sufficient weld time. An increase of the weld time will decrease the DBTT. This may be caused by a healing effect of the crystal lattice in the weld region during the second step. Of course such a healing effect will be accelerated by an increased process temperature. Now the question, why a first step is necessary, has to be discussed. It could be considered to develop a U-DW process using 1050 °C at 10 MPa, for instance. The answer is very simple. Our tensile results show softening, and an extended process time at high temperature will increase this change to an unacceptable degree. For the lower temperature the pressure of 10 MPa is not sufficient for the necessary levelling of the long range surface roughness, as discussed in chapter 2.4.1. Process parameter chosen this way would eliminate the visco-plastic creep rate. So a second process step would be required again with a different pressure value.

In addition the degree of CD of about 6% is one-half of that for a comparable one-step process. This is the vitally important advantage of the two step U-DW process.

3. Conclusions

The results presented here show that the use of a two step U-DW can increase the weld quality by decreasing the DBTT. It is possible to generate perfect U-DW welds with a single or a two step process. However, the two step U-DW process shows the fundamental advantage of decreased compressive deformation of the work piece. The applied heat treatment of the U-DW process causes an additional irreversible change of tensile properties resulting in lower yield strength (90% of the as delivered state) and an increased failure tensile strength of the base material. The fracture toughness of the welds reaches 95% of the base material. The DBTT is increased by 7 °C in contrast to the base material which is nearly negligible. This has to be considered in future design proposals. These results should also be transferable to a HIP process. The minimum necessary bonding pressure for the first step has been determined to be between 18 and 20 MPa. This paper presents results of non structured small U-DW samples. The transfer of this process to real plates with cooling channels will be a challenge for the future. We hope to publish the results soon.

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