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Material flow control in tailor welded blanks by a combination of heat treatment and warm forming

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ABSTRACT

A new process design for manufacturing high strength aluminum structural parts from tailor welded blanks is presented. After an initial friction stir welding the sheet material is post weld heat treated and finally warm formed in a stretch forming operation. Plastic material behavior and the forming limits are studied at elevated temperatures. Numerical and experimental investigations are carried out to determine the material flow with respect to the heat treatment condition as well as the forming parameters. This fundamental knowledge is used in a numerically based process design to improve the formability and the final part properties.

1. Introduction

High strength aluminum alloys have proven their potential for lightweight structural parts in aerospace as well as automotive industry [1]. Since their formability is limited, temperature assisted manufacturing processes like e.g. warm forming are used to shape sheet metal parts [2]. Another approach for cost efficient weight reduction in vehicle structures is the application of the tailor welded blank technology. Tailor welded blanks (TWB) are a class of semi-finished products characterized by the combination of sheet materials with different thicknesses, material properties or coatings into a single sheet optimized for the forming operation or the case of application [3]. As some aluminum alloys show bad weldability in terms of fusion welding, friction stir welding (FSW) is used to successfully join these materials. In FSW the material is mixed and joined with stirring of a tool below melting temperature whereby hot crack sensitivity is avoided and sound welds can be produced [4]. The relevance of FSW, especially for assembly welding of structural parts, was considerably growing during the last 20 years [5]. Moreover the potential of friction stir welded TWB has been analyzed in sheet forming applications like conventional deep drawing [6] and superplastic warm forming [7]. Approaches for the numerical formability prediction in dome stretching and cup drawing based on local flow behavior and forming limit analyses in cold forming conditions have been presented [8]. Hence the thermomechanical FSW process transforms the initial microstructure and generates a property gradient across the weld line which has to be considered in the manufacturing process.

2. Process chain based on aluminum tailor welded blanks

A process chain for manufacturing structural parts based on TWBs offers the advantages of improved part properties and high cost efficiency by part integration instead of complex assembly welding of 3D-shaped parts. Beginning with FSW of flat aluminum sheets the resulting TWB is shaped in a warm forming process (WF) and undergoes a solution heat treatment (SHT) with subsequent water quenching (WQ) to generate a supersaturated microstructure with hardening potential. The part strength is finally improved by an artificial aging (AA) (see Fig. 1). Homogeneous properties are obtained across the whole part as no further welding operation has to be performed. Nevertheless this process chain exhibits challenges caused by the inhomogeneous material properties in the weld area of the TWB. A strength difference between base material and weld nugget affects the forming limit and leads to an inhomogeneous sheet thickness distribution due to unequal flow behavior [9].

Previous investigations have proven the possibility to modify aluminum sheet properties by applying a tailored heat treatment prior to forming. In heat treatable aluminum alloys, i.e. AA6016, the effect is based on the dissolution of precipitates within a heat treatment between 190 and 280 °C [10]. Hence the implementation of an additional post weld heat treatment (PWHT) into the prescribed process chain aims to adjust the forming behavior of the weld line material to overcome the limitations of local formability.

This paper presents the main achievements of the investigation on the formability of Al-Cu friction stir welded tailored blanks conditioned in a PWHT prior to forming. The aging sequence of Al-Cu-alloys is known as: supersaturated $\alpha \rightarrow$ GP zones $\rightarrow \theta'' \rightarrow \theta' \rightarrow \theta$. However friction stirred material consists of an undefined state of precipitates caused by welding heat and severe deformation. The analyses are focused on identifying a suitable process window for the heat treatment and forming operation based on microstructure, hardness and mechanical property investigations. A numerically based process design for the control of the material flow in plane and in thickness direction locally in the weld area is used to enhance the formability and adjust the sheet thickness distribution.

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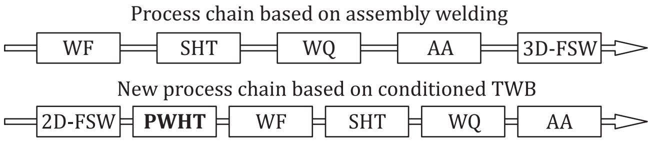

Fig. 1. Process chain for manufacturing high strength structural aluminum parts with additional post weld heat treatment (PWHT).

3. Investigation approach and analysis

The investigation approach is divided into two steps. First a basic analysis of the material characteristics due to the initial welding and the subsequent PWHT aiming for understanding the principle mechanisms to be able to define a suitable process window. Second part is dealing with the characterization of the local material behavior and a transfer to a numerically based process design for a stretch forming operation.

Plates of AA2219-O and AA2195-O with an initial thickness of 12 mm were butt welded on a four-axis CNC milling machine Heller MCH250 at IWB, Munich, Germany [11]. The tool consists of a 26 mm diameter shoulder and a threated conical pin with a length of 11.8 mm. A double path welding strategy was used to create symmetric weld properties, while the welding direction was orientated parallel to the rolling direction of the sheet. As base parameters a rotation speed of 5.83 s^{-1} and a velocity of 2.08 mm/s were chosen in a force controlled welding setup. To be able to perform standardized forming analyses sheets with a thickness of 2.5 mm are worked out of the initial plates by CNC-milling 6.5 mm from the shoulder side and 3 mm from the bottom side of the weld (see Fig. 2a).

A PWHT is performed in an electrically heated radiator furnace type LINN KS-240. Specimens are heated up within 1 h and afterwards kept constant at the post weld heat treatment temperature T_{PWHT} for another 60 min. T_{PWHT} is varied between 200 and 450 °C in steps of 50 K. As alloyed aluminum materials tend to build a time and temperature sensitive supersaturated microstructure when cooled rapidly or quenched, a slow cooling rate of 30 K/h in the furnace is set above 150 °C. Temperature is controlled by thermocouples type K which are mounted directly on the specimens so that the deviation of maximum temperature during dwell time is limited to ±3 K.

After PWHT the properties of base material (BM), heat affected zone (HAZ) and weld nugget (WN) are analyzed. For micrographic analysis and hardness measurements weld line material is cut out of a blank by water cooled metal cutting and embedded in epoxy resin and finally surface grinded and polished with 6, 3 and 1 μm compound. The hardness of the cross section is measured on a testing machine Zwick HV10 with a load of 10 N and a resolution across the weld line of 1.0 mm. With regard to the FSW tool geometry and micrographic analysis in Fig. 2a as well as the hardness mapping in Fig. 2b the section ±5 mm around the joint line is assigned to WN and points >15 mm away from the center are ascribed to BM. In between an average hardness value of the HAZ is calculated between 6.5 mm and 10.5 mm distance to origin. In addition differential scanning calorimetry (DSC) is performed on a Mettler Toledo type DSC822e in stainless steel pans with BM and WN specimens with a heating rate of 0.15 K/s.

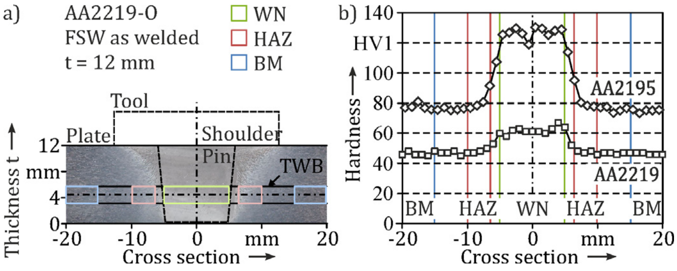

Fig. 2. AA2219-O friction stir weld line with (a) microstructure and (b) hardness distribution dependent zone definition in tailor welded blank.

The formability was tested with miniaturized tensile specimens in a universal testing machine Zwick Z100 with conductive heating unit [12]. Forming limits curves (FLC) were determined in a Nakajima testing device with a punch diameter of 100 mm for room temperature, 150 °C and 200 °C with selected specimen geometries as suggested for warm testing [13] to represent uniaxial (UA), plane strain (PS) and biaxial (Biax) straining. The punch velocity was set to 0.7 mm/s which results in an average strain rate of 0.01 s^{-1}.

Final forming tests of TWBs conditioned by PWHT are performed in comparison to base material and as welded blanks with the Biax-geometry of the Nakajima setup. Forming temperature of 150 °C is applied while the resulting strain distribution is measured optically with an ARAMIS® system. Specimens are strained to fracture with a punch speed of 0.7 mm/s. After forming the geometry is digitalized with an ATOS® system to exactly determine the sheet thickness distribution and the crack location.

4. Process window for PWHT

Welding overaged aluminum blanks results in weld lines with increased hardness compared to the base material. The initial Vickers hardness of the base material (HV_{BMaw}) is 46.2 HV1 ± 1.0 HV1 for AA2219 and 77.7 HV1 ± 0.9 HV1 for AA2195 while the weld nugget hardness is 34% respectively 62% higher. These gradients are taken as a reference to quantify the effect of the PWHT (see Fig. 3a). Above 200 °C the weld nugget of both materials is significantly softened in a linear trend up to a maximum temperature of 350 °C for AA2219 and 400 °C for AA2195. At the same time hardness of BM and HAZ exhibit only a slight reduction compared to the initial state due to the already overaged structure. Further increase of the heat treatment temperature to 450 °C leads to undesirable severe grain growth which delimits the process window. For all sampling points the HAZ shows no significant difference to the BM so that these zones are not distinguished in the following analyses.

The analysis of the heat flow Φ in DSC tests gives a deeper insight into the physical mechanisms during PWHT (see Fig. 4). Plotting Φ over the heat cycle temperature the overaged base materials display a single endothermic peak at temperatures above 300 °C which is in accordance to [14] mainly due to dissolution of the predominant θ structure.

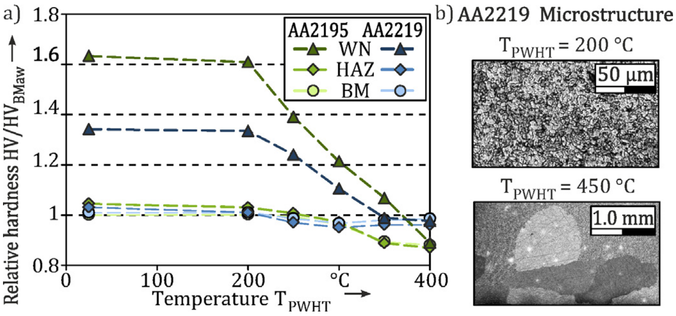

Fig. 3. (a) Softening effect of PWHT in weld zones visualized in percentage of the base material hardness in as welded condition and (b) weld nugget microstructure after PWHT.

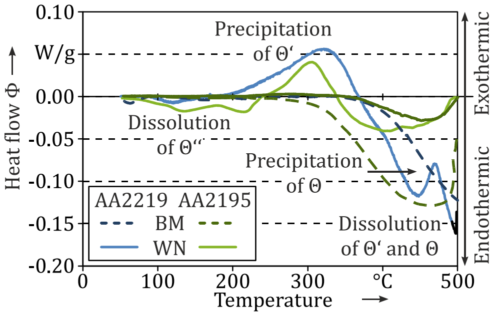

Fig. 4. DSC analysis of AA2219 and AA22195 base material (BM) in O-condition and weld nugget material (WN) in as welded condition.

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