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Numerical analysis of electron beam welding of different grade titanium sheets ☆

Konrad Adamus *, Zygmunt Kucharczyk, Kwiryn Wojsyk, Krzysztof Kudla

Czestochowa University of Technology, Faculty of Mechanical Engineering and Computer Science, ul. Dabrowskiego 69, 42-201 Czestochowa, Poland

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ABSTRACT

In the paper the numerical analysis of a titanium sheet welding process was presented. During the welding process sheets made of titanium Grade 2 and Grade 5 were joined using electron beam welding technology. The result of the welding operation was tailor welded blank which in the next stage of processing was formed to produce a final part of an aircraft. Tailor welded blanks are made of dissimilar materials and as a result they have mixed properties of their constituent materials. Titanium Grade 2 provides good formability and can be used for those parts of a blank which are susceptible to cracking during a forming process. Titanium Grade 5 provides high strength. Electron beam welding is a fusion welding technology which is characterized by a high power density heat source, high quality of joints, a wide range of weld depths and a small heat input.

For the purpose of the simulation finite element method was used. A thermo-elastic–plastic material model was assumed. The main difficulty in simulating the process of thin sheet welding is sheets' tendency to significant deformation as a result of thermal expansion. In the paper different factors contributing to transverse and longitudinal bending were analyzed. It was shown that introduction of a welding gap into the model facilitates capturing transverse bending deformation. The impact of transverse bending on longitudinal bending was analyzed. The effect of mesh density and element type on transverse bending was analyzed. The calculated deformations were compared against the experimental results. The calculated temperature and stress fields were also presented.

1. Introduction

The goal of this work is to build a numerical model predicting the evolution of temperature, stress and displacement fields for thin titanium sheets that are joined using electron beam welding, EBW, technology. The joined sheets will be used as tailor welded blanks and will undergo forming process to produce a final sheet part of an aircraft.

1.1. Electron beam welding

EBW is a technology that uses electrons to join materials [1,2]. The welding process consists in accelerating electrons using electric field and directing them onto the surface of welded objects. Upon the collision kinetic energy of electrons is converted into heat. Electrons have the capability to penetrate material at depth of about 10^{-2} mm, however it is possible to create welds of depth up to 300 mm. This follows from the fact that the amount of heat produced by electron collisions is so large that the material is unable to transfer whole heat using conduction. The material starts to melt and subsequently vaporizes. A narrow and deep cavity filled with metal vapor is formed. The electron beam penetrates trough the cavity and can access deeper layers. The mechanism of beam transport trough the cavity allows for achieving welds that have the ratio of depth to width up to 10:1.

EBW units offer a wide range of beam powers from 0.5 to 300 kW. This allows for achieving a wide range of weld depths from 0.2 to 300 mm. The electron beam has high power density equal to about 10^7 W/cm^2. High values of beam power allow for creating welds with a minimal heat input which results in a minimal size of the fusion zone, FZ, and the heat affected zone, and small distortions. The application of a vacuum chamber allows for joining materials that are susceptible to interactions with atmospheric gases such as titanium. Another advantage of using EBW is its capability to weld materials that reflect a laser beam.

Modern EBW units are capable of self-diagnosis [3]. The measurement system comprising hole, slit and rotating sensors provides information about the electron beam quality and allows for maintaining appropriate beam parameters during a welding

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* Corresponding author. Tel.: +48 609 077 013.
E-mail address: konrad.adamus@gmail.com (K. Adamus).

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process. The system can be used for three-dimensional welding trajectories where the distance between a workpiece surface and an electron beam gun changes and control parameters must be adjusted to maintain the specified beam spot size. A multiple beam variant of EBW technology was suggested by Zhao et al. [4]. A deflection system is used to produce three separate beams, the first beam preheats a workpiece, the second beam creates a weld and the third beam smoothes the weld.

EBW is used in the aircraft industry for the purpose of joining turbines, landing gear made of high strength steel, structural and load bearing parts made of aluminum and titanium alloys.

1.2. Simulation of welding distortion for plate structures

The knowledge of post-welding distortions in a structure is important for engineers to properly design a welding process. From the point of view of numerical simulations the task of predicting deformations is more difficult than predicting residual stresses [5]. A prediction error in displacements will translate to a smaller error in stress values since strain hardening modulus has low value compared to elasticity modulus and the maximal values of residual stress tend to be near yield stress. The accuracy of a simulation is dependent not only on a material model but also on a clamping device model, a welding gap model and selection of an appropriate FEM mesh.

Deang and Murakawa [6] analyzed modeling of a process that consisted in welding large and complex structures made of thin plates. The welding process involved positioning of the plates that resulted in a tight contact relationship. In order to take into account contact, slide and gap between parts interface elements were used. Equations describing a relationship between stresses and displacements in the interface elements use parameters defining maximum bonding force per unit area, shape of stress–displacement curve, precision in positioning and the size of a gap remaining at the welding stage. The numerical model combines a thermo-elastic–plastic FEM model and a large deformation elastic FEM model that treats residual plastic strains near the weld zone as inherent strains.

Yang and Dong [7] analyzed buckling distortions occurring in 2.5-mm thick steel sheets as a result of a welding process. The welding process involved using a clamping device to fix the sheets. A thermo-plastic material model was assumed. The mesh was built from 3D shell elements. It was noted that the shape of the deformed sheets obtained from the thermo-plastic model with respect to longitudinal bending does not match the actual shape of the sheets after welding. Thus in order to capture buckling distortion full-field residual stress distribution obtained from the thermo-plastic model was used as an input to a 3D buckling analysis model. The buckling analysis comprised residual stress analysis, selection of the most likely buckling mode and performing post buckling analysis.

Heinze et al. [8] investigated the sensitivity of a numerical model predicting distortions induced in 5-mm thick steel plates by a welding process. The model used in the analysis coupled thermo-metallurgical and mechanical calculations. Force-free support was used during the process and in the model it was represented using elastic constrains at plate corners. The model sensitivity was investigated with respect to mesh structure. It was found out that mesh coarsening in the transverse direction with increasing distance from the weld is not preferable for calculating distortions. On the other hand mesh coarsening in the thickness direction with increasing distance from the weld facilitates the calculation of distortions. Modal analyses were performed to determine structure stiffness for different meshes. It was fond out that these analyses can be used to assess the impact of element edge size on the deformation of certain mesh types. However for the assessment of the impact of mesh type modal analyses should be accompanied by mechanical analyses.

2. Material and methods

Titanium properties and its industrial applications are described in [9,10], Titanium is used in different industries due to its combination of corrosion resistance, heat resistance and high specific strength. Application of titanium in aircrafts as an alternative to steels and aluminum decreases construction weight and provides better weight efficiency. Titanium is essential in supersonic aircrafts where aluminum has too low heat resistance and steels have too high density.

During the EBW process two titanium sheets were joined. One sheet was made of titanium Grade 2 and the other of titanium Grade 5. Grade 2 is commercially pure titanium (99.2 wt.%). The strength of commercially pure titanium is increased by the presence of oxygen, and to smaller extent, by the presence of iron, carbon and nitrogen. These elements influence also the temperature of titanium polymorphic transformations. The yield stress is in range 275–410 MPa.

Titanium Grade 5 is alpha–beta alloy containing 6% aluminum and 4% vanadium. Vanadium acts as the stabilizer of beta phase at lower temperatures. Grade 5 has higher values of stress–strain curve than Grade 2. The minimal yield stress may be in range 760–895 MPa depending on processing, heat treatment and chemical composition (especially oxygen). Grade 5 has lower value of thermal conductivity at room temperature (6.6 W/mK) than Grade 2 (20.8 W/mK). Both Grade 2 and Grade 5 have similar values of coefficient of thermal expansion and specific heat.

Aircraft components have to be optimized with respect to low weight, low assembly costs and right material depending on the function of a component. These objectives can be achieved by manufacturing components from dissimilar material sheets joined using welding technologies – tailor welded blanks, TWB. TWB undergo further forming processes to produce a part that has mixed properties of its constituent materials. Titanium Grade 2 provides better formability and can be used in areas that are susceptible to cracking during forming process [11]. On the other hand titanium Grade 5 provides higher strength. The weld joining sheets is an important factor having an impact on the quality of a TWB deep drawing process.

Weldability of titanium is described in [10]. The main problem during welding of titanium is its tendency to absorb oxygen, hydrogen and nitrogen at temperatures above 427 °C. The excess absorption of these gases causes titanium embrittlement. The problem is solved by application of either inert shielding gases (argon) or a vacuum chamber. Unalloyed titanium and alpha alloys are weldable. For alpha–beta alloys, weakly beta-stabilized alloys (titanium Grade 5) are also weldable, heavily beta stabilized alloys become embrittled during welding. The embrittlement is caused by formation of alpha' martensite.

Fig. 1 presents the welded sheets made of titanium Grade 2 and Grade 5. The welding process comprised two parts. First a tack weld was created at the one end of a welding gap. Subsequently main welding pass was performed starting at the other end of the welding gap towards the tack weld. The purpose of the tack weld is to prevent the sheets from moving away in opposite directions as a result of thermal expansion caused by a moving heat source. During the EBW process the following parameters were used: beam current – 4 mA, accelerating voltage – 50 kV, welding speed – 20 mm/s. Both sheets have thickness of 0.8 mm and length of 158 mm. The sheet made of titanium Grade 2 has width of 28.5 mm and the sheet made of titanium Grade 5 has width of 26 mm.