Experimental Verification of Knowledge-Based Welding Distortion Estimation Method

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Abstract. Automation of welding robot programming is a method to improve the productivity of multi-robotic welding production. However, robotic welding off-line programming and simulation software packages often neglect the effect of the welding distortions to a workpiece, which is one of the main problems during jigless assembly in multi-robot welding. Therefore, knowledge-based information of the amount of welding distortion is often required for the off-line programming of a jigless multi-robot welding to be successful. This paper assesses a knowledge-based welding distortion estimation method through practical verification experiments. The measured angular distortions, from preliminary welding experiments, were used as a basis for setting the preset angle and modifying the position of the handling robot in the verification welding experiment. The results indicate that the consistency in achieving the required preset angle during part positioning and the consistency of the amount of angular welding distortion, is sufficient to beneficially exploit the welding distortion in obtaining perpendicular fillet weld joint geometry, which fulfils the tolerances set in standards EN ISO 5817 and EN ISO 13920 respectively.

Keywords: Jigless welding · Multi-robot welding · Welding distortions

1 Introduction

Drive for increasing the level of automation and autonomous production in welding has led to the development of multi-robotic welding cells. The cells consist of at least one welding robot and one part handling robot. Recently the research has focused on task handling and jigless assembly on multi-robot cells. [1–4] The cost-effectiveness of using robotic welding is highly dependent on the robot utilization rate. Especially, when welding is considered, the indicator arc-on time is a key factor. In low-volume or single batch production the robot utilization rate and arc-on times are typically low, due to the fact that product variation is common and set up times for a new type of product take a great portion of total manufacturing time. The use of multiple robots and jigless or flexible assembly has been seen as key technologies to increase utilization and arc-on time in low-volume and single-batch robotic welding production. [2, 4] In this research jigless multi-robot welding cell is used as a research environment for the practical welding experiments.

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The state of the art in welding robot programming is that the robot programs are made with off-line programming and simulation software. Off-line programs are a series of robot statements created in a robot programming software on a computer. However, the robotic welding simulation environment and the CAD workpiece are ideal, which means that the off-line programs will inevitably have inaccuracies in them in a physical station. Furthermore, during welding, heat input of the welding process forms thermal expansions and contraction creating angular deviations and distortions into the final product, which further creates error between the off-line programmed program and the actual required program.

Welding distortions are typically unwanted byproducts of welding production. The formation mechanisms of welding distortions are known, but the phenomenon is quite complex due to the multiple metallurgical, time, heat, cooling, stress and strain-related factors. [5, 6] For the T-joint type of weld, angular distortion is the expected type of welding distortion. The main mechanism of angular distortion is the result of shrinkage perpendicular to the weld. The typical estimation method is finite element (FE) simulations. Various research topics in the field focus on developing computational welding methods (CWM), such as the thermo-elastic-plastic method and inherent strain (local-global) method. CWM requires a high level of computational time and expertise to master the model and to get accurate estimation results. [5] FE-simulations can give a numerical value of angular distortion and is an effective tool in minimizing them in the welded structure. However, in the view of manufacturing/production operations, welding distortions are prevented in more practical methods. For example, controlling heat input, controlling welding sequences, using fixtures, tack welding, using symmetry during welding, increased working temperature, heat straightening and presetting parts. [5–9] Considering multi-robotic jigless welding, the presetting of parts to a certain angle in T-joint is a method that can be intelligently executed based on the knowledge of welding distortion and therefore to be used in the off-line programming software in modifying robot programs to estimate angular distortion.

This paper continues the study of previous research of knowledge-based welding distortion estimation method for a multi-robot welding off-line programming and simulation software. In previous research [4] a method for the functioning of a knowledge-based welding distortion estimation method was developed, in which measured angle between two workpiece plate parts, before and after the welding experiment, was used to modify handling robots' position for the known amount of angular distortion. It was also verified in simulation, that the handling robot is able to modify its program and position according to the measured and analyzed correction angle.

The research problem is that the previous research did not verify whether the angle between joining surfaces of the corrected workpiece will be in the correct position after welding. Therefore, the question remains if the knowledge-based welding distortion estimation for presetting the workpiece is consistent enough and if the angular distortion remain consistent when the preset angle between plates changes. To overcome the research problem, the aim of this paper is set to verify with practical welding experiments, that the known amount of angular distortion can be used for presetting the top plate of the T-joint so that the resulting post-weld angle between plates will be perpendicular and in between the tolerances set by EN ISO 5817 and EN ISO 13920.

2 Methods

To conduct this research two research methods were used. At first, a jigless multi-robot welding experiment was carried out to find out the required correctional preset angle to compensate for the angular distortion. Then, a knowledge-based controlled welding distortion estimation methodology, developed in Lund et al. 2020 [4], was used. The functioning of the knowledge-based controlled welding distortion estimation methodology was verified with jigless multi-robot welding experiments and analysis of the suitability of the methods to the estimation of welding distortion in off-line programming was carried out based on the verification results.

The physical experiment environment was a jigless multi-robot welding cell. The cell was implemented with two Motoman robots and a two-axis L-table MT1-1000 S2X. The robot used for part handling tasks was ES165N and the robot used for welding and optical measuring tasks was EA 1900. The cell also consisted of welding power source Kemppi A7, computer, Delfoi robotics 4.3-software and Winteria-software. The welding robot was equipped with a laser-line scanner, Micro-Epsilon ScanControl 2960-50. The handling robot was equipped with a magnetic gripper. The two-axis L-table was equipped with a magnetic positioning system. The whole robotic system was controlled by a pair of NX100 controllers. MotoNIS (Motoman Network Information Server) was used for communication with workstations when running a custom computer code, for instance during laser scanning and gathering positional information. The virtual experiment environment was a digital twin of the physical jigless multi-robot welding cell and the experiment environment was modeled in Delfoi Robotics 4.3 software. CAD-models of robots' equipment and workpiece were imported to the Delfoi Robotics, where each component's and robot's functionality were implemented.

The experimental process in this research can be divided into five phases, initial condition, knowledge, control, verification and analysis phases, as presented in Fig. 1. In the initial condition phase, robots were programmed in an off-line programming environment and the programs were post-processed and downloaded to the robot controller. In the knowledge phase, the initial program was run and measurement data for calculating the amount of angular distortion was collected. In the control phase, the median value of the angular distortion was used in the calculation of the preset angle value and robot programs were modified to adapt to the new position. In the verification phase, similar steps were carried out as in the knowledge phase, but this time the plate was positioned at the preset angle prior to welding experiments. Verification tests were run three times to see if the results were consistent and if perpendicular T-joint can be achieved, within the tolerance set by standards. In the analysis phase, the results were reviewed from the viewpoint of consistency and to answer the research questions.

The welding experiments were performed in a single pass in the full length of the workpiece. Workpiece plates were tack weld to hold plates in place. The used welding position was a horizontal fillet weld position, also known as PB/2F position, and the welding process used was GMAW. The welding parameters for each weld were as follows: welding current 232 A, voltage 26.2 V and welding speed 9 mm/s. Workpiece consisted of two hot rolled S420 grade steel plates with a thickness of 5 mm and the size of 225 $\times$ 250 mm.

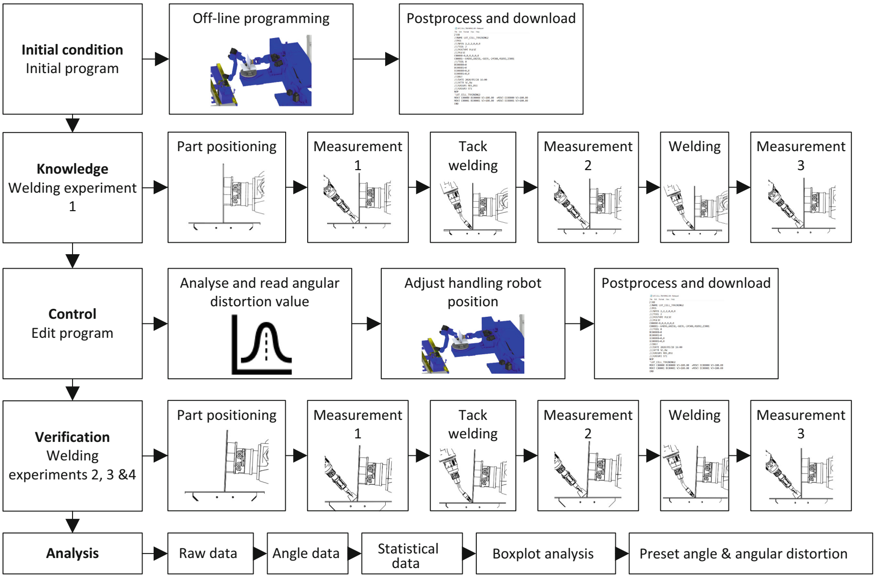

Fig. 1. Experimental process and process steps.

The empirical inquiry of the study consists of the evaluation of the accuracy and consistensy of estimating the welding distortions based on the knowledge of angular distortions gathered from the preliminary welding experiment. Three welding experiments were conducted to test the functionality of the method. Ideally, after fillet weld, the angle between the base plate and the top plate should be perpendicular, but the standards EN ISO 5817 and EN ISO 13920 give certain tolerances for the perpendicularity of the fillet weld joint geometry, which will be the tolerance criteria that must be fulfilled. For workpiece dimensions of height 225 mm and width 250 mm the standard EN ISO 5817 gives tolerance values for perpendicularity of $\pm$ 1° and EN ISO 13920 gives tolerance values for perpendicularity of $\pm$ 0.75°. The joint was laser scanned in each phase of the experiment and the raw data of fillet weld joint geometry were first analyzed using the Winteria weld geometry analysis software. The software transformed the raw data to angular data, which were then further analyzed in MATLAB software. Statistical analysis was implemented to the angle data to evaluate the consistensy of the knowledge-based welding distortion estimation method. The median values of the measured angles were analysed and then used for calculating the angular distortion and the preset angle. The plate was assumed to be linear throughout its length before welding and in tack welded state. In a post-welded state, the plate was assumed to be linear enough, so that the median value of angle can be used in the calculation. Standard deviation to angle data was calculated to verify that the median angle value represents the complete angle of the joint. Then, a boxplot analysis to post-weld fillet weld joint angle data was carried out, to compare the median angle values to the tolerance limits set by standards. Finally, the medians of preset angles and angular distortions consistency to achieve the targeted values were compared.

3 Results and Analysis

Results of the preliminary welding experiment were measured with an optical sensor and analyzed, first in Winteria weld geometry analysis software to get the angle data, and then in MATLAB for further analysis. The measurement results for verification were handled in a similar practice. Figure 2 and Table 1 show the results of measurements in welding experiments 1–4. The measurements in preliminary welding experiments showed that the medians of the plate angle prior to tack welding was 90.969º, after tack welds 91.026º and after welding 88.740º. This means that the welding distortions caused the plate angle to change 2.229º. Therefore, 92.229º was set to be the target for preset angle of workpiece plate 2. In welding experiments 2–4 the median angle between plates before tack welding were 92,682º, 93,576º and 92,449º in respective order. The median of plate angles after tack welding in welding experiments 2–4 were 93.232º, 93.484º and 92.485º in respective order. In welding experiments 2–4 the median plate angles after welding were 90.642º, 91.232º and 90.130º in respective order. Therefore, the welding distortions have changed the plate angle in welding experiments 2–4 2.040º 2.343º and 2.319º in respective order.

The target for median preset angle before welding was 92.229º and the closest attempt to the target median preset angle was achieved in welding experiment 4, which was 0.220º over the target. The furthest attempt to the target was in welding experiment 3, which was 1.347º over the target. The welding distortions caused by tack welding had only a minor pulling effect on the angle between plates, under 0.1º, except in welding experiment 2, where the tack weld had increased the angle by 0.546º, meaning the tack weld had pushed the joint to open. The standard deviations of welds were quite low as can be seen from Table 1, which was an expected result, as the measured objects were plates. A boxplot analysis was carried out to visualize how the results of welding experiments 1–4 fit in the tolerance limits set by the standards. The boxplot analysis is presented in Fig. 3 a). It can be seen that the median values of the measured angle were between the acceptable tolerance values in experiments 2 and 4. Experiment 1 was the initial experiment and the resulting angle between plates was not expected to be within the tolerance range, and the analysis shows that it exceeded the tolerance range. In experiment 3 the targeted tolerance values were not achieved, which may be a result of a measurement error, as the measurement range is clearly wider than in the other experiments. Experiment 3 was also the only experiment where the boxplot analysis show the occurrence of outliers. From Fig. 3 b) it can be seen that the angular distortion values were consistently close to each other in each experiment even though the achieved preset angle varied a bit between experiments. The range of median angular distortions were only 0.303º, while the range of median preset angles were 2.607º.

4 Conclusions

In this research, a knowledge-based welding distortion estimation method was tested and verified by practical welding experiments in a jigless multi-robot welding cell. The required modifications to robots' position, during presetting of the workpiece to a certain angle, can be initialized in the off-line programming and simulation environment, with

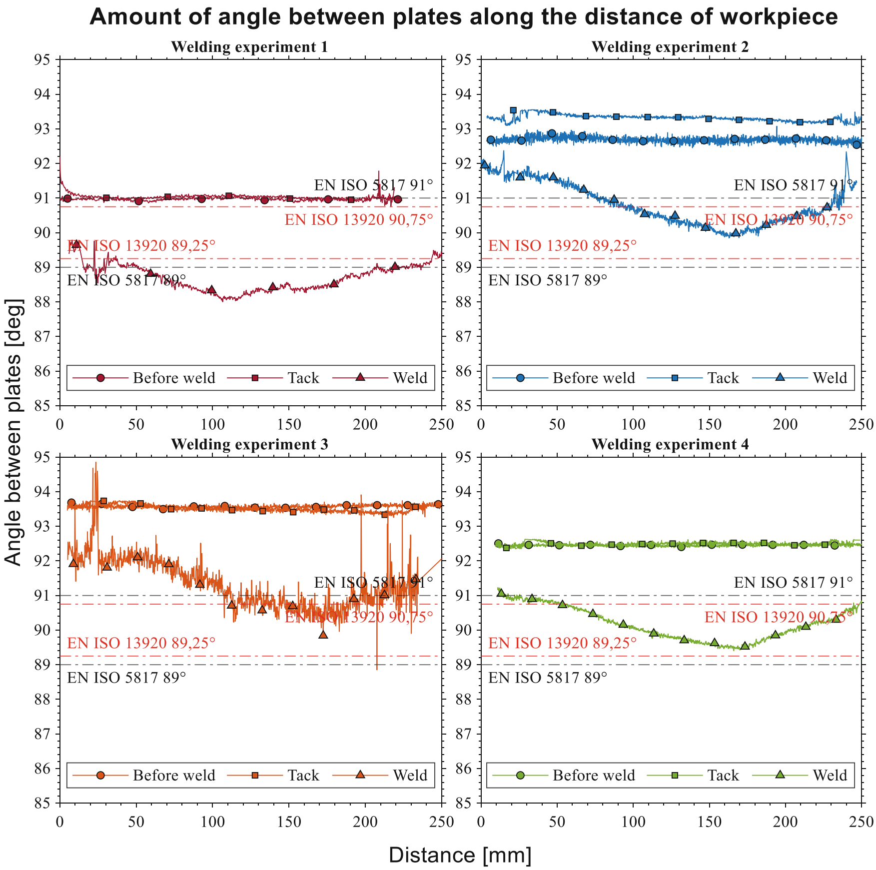

Fig. 2. Amount of angle between workpiece plates in welding experiments 1–4.

the methodology presented in the earlier study of the subject [4]. The primary concern of this research was that if the angular distortions will be consistent enough to achieve perpendicular fillet weld T-joint geometry when workpiece is offset by the amount of correction angle from perpendicularity.

The results indicate that with the knowledge-based welding distortion estimation method the perpendicular fillet weld T-joint geometry can be obtained within the tolerance set by standards. The consistency was not fully achieved, as only two of the three verification experiments met the tolerance limits. The experiment in which the tolerance limits were exceeded (welding experiment 3), suffered from fuzzy measurement data and outliers, which may have affected the results failure. Furthermore, in welding experiment 3 the highest preset angle was measured, which may have also affected the results failure. Nevertheless, the measured angular distortion of welding experiment 3 was close with the rest of the experiments and the exceeding amount was just 0.2º over the tolerance limit of EN ISO 5817. In a typical production environment, such a small

Table 1. Statistical results of welding experiments 1–4

Experiment	Phase	Mean [°]	Median [°]	STD	Correction angle [°]
1	Before welding	90.969	90.969	0.0389	
	Tack weld	91.03	91.026	0.088	
	Weld	88.732	88.740	0.395	2.229
2	Before welding	92.685	92.682	0.077	
	Tack weld	93.317	93.323	0.085	
	Weld	90.788	90.642	0.595	2.040
3	Before welding	93.575	93.576	0.042	
	Tack weld	93.497	93.484	0.090	
	Weld	91.32	91.232	0.684	2.343
4	Before welding	92.451	92.449	0.028	
	Tack weld	92.486	92.485	0.046	
	Weld	90.19	90.130	0.479	2.319

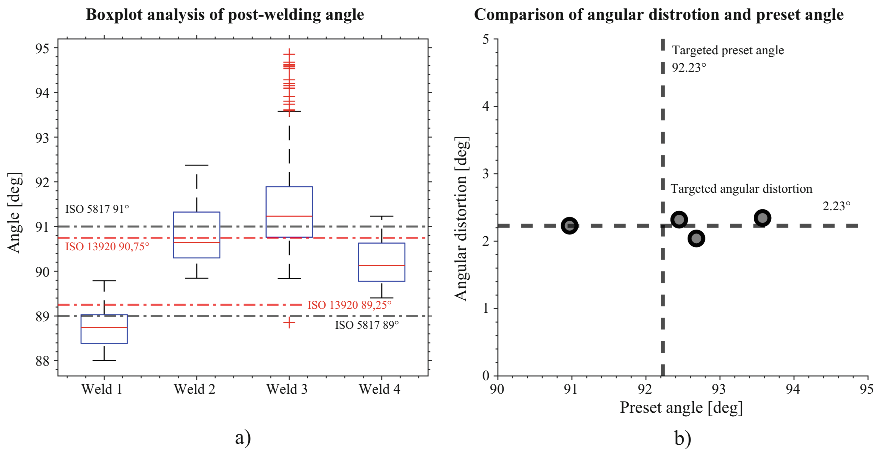

Fig. 3. Boxplot analysis a) and comparison of angular distortion and preset angle b)

exceeding would most likely have gone unnoticed, as manual measurement is the state-of-the-art in most quality assurance operations. A question arises if the mesurements should be repeated when fuzzy or non-consistent measurement is noticed.

Another interesting finding was, that the median angular distortion values remained in a range of 0.303° to each other, even thought the median preset angle values varied in a range of 2.607°. This indication highlights the importance of reaching the right preset angle value during positioning, as the angular distortion seems to remain consistent as long as welding conditions, with a exception to a preset angle, remains constant.

In a broader perspective, the results are a promising step towards the development of more flexible and productive low-volume or single batch robotic welding production. The further development of knowledge-based welding distortion estimation method to a automated programming tool for off-line programming software can contribute to a decrease in set up time and material handling times, thus, increasing the utilization rate of welding robots and arc-on time.

Further research on different types of T-joint welding procedures is required to evaluate the methods usability and reliability. For example, welding of T-joint with both sides fillet welded, multipass welding and welding of workpieces with multiple different material thicknesses.

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