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Application of Additive Manufacturing for the Repair of Forging Dies

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Abstract

In this paper the investigated conditions and possibilities of repairing forging dies with high precision robotic MAG welding are presented. Different welding wire electrodes were examined and compared by their processability. Productivity, process stability, slag and fume formation were in the focus of investigation. Metallographic tests were carried out to validate the compliance of welded layers. Based on the performance of the wire electrodes, recommendations have been elaborated for the procedure specification and also for further investigation. Some robot cell layouts have been designed adapting to the special working environment and requirements of the welding procedure.

Keywords*: : additive manufacturing, wire arc additive manufacturing, robotic welding, hardfacing.*

1. Introduction

1.1. Purpose

Flexman Robotics Ltd's customers have been interested in robotising the repair welding of hot work tool steels in order to increase the accuracy of the welding material application, thus reducing welding and machining time and related costs. The goal of the research was to find suitable welding material and develop a related welding technology and robot system. For this purpose, experiments were carried out to evaluate the weldability of the tool steel to be repaired, while measuring the factors that mainly influence the usability of the examined welding materials and the reliability of the technology. Then, the hard layers were subjected to metallographic examination to validate the technology used.

1.2. Main characteristics of overlay welding

Overlay welding is a widely used technique for maintenance and repair tasks, as well as for the manufacture of products whose surface properties must be substantially different from those of the cross-section, this process is known as hardfacing. When overlay welding is used, typically the entire surface is welded in one or more layers, or when material deficiencies are replaced, the surrounding area is partially or completely removed, and a much larger portion than the original discontinuity is being welded. In order to increase accuracy, a company carrying out hardfacing or overlay welding has a strong economic interest. Welding materials for hardfacing are very expensive, and the welded excess material must be subsequently removed by machining, which is also very costly since these materials are generally difficult to turn **[1]**.

Precision is a connecting factor between conventional overlay welding and additive manufacturing, which usability we have previously analysed in detail **[2]**. Significant advances have been made in the field of wire and arc additive manufacturing (WAAM) in recent years. Practical applications are gaining ground and the number of high-precision tool repair companies is increasing **[3–5]**.

1.3. Weldability examinations

The professional repair of tools exposed to wear and attrition can bring significant benefits, as beyond the original quality, careful selection of welding materials and technology can extend the life of the original. A tool can be repaired multiple times, so well-designed repair-overlay welding technology is very cost-effective **[6]**.

Tool steels can be divided into two major groups in terms of welding: high-alloy and medium-alloy and non-alloy tool steels. Most of them remain soft, austenitic for a long period of time after cooling from the quenching temperature to the preheat temperature for about 30 minutes. Staying in this temperature range can work for several hours without the risk of cracking. This is a commonly used and highly reliable method for welding high or low alloy tool steels, however, such a high degree of preheating is not always permissible [1]. The examined tool steel is designated according to EN ISO 4957 as 55NiCrMoV7 (short code: 1.2714), a forging tool made of tool steel cannot be preheated to this high temperature range. A number of methods have been developed to determine preheating and the associated specific heat input, but due to the high carbon equivalents they may not be used, or only with special considerations. Several of these are hereby examined, however, only two will be presented: the Kasuya–Yurioka and the Béres methods.

1.3.1. The Kasuya–Yurioka-method

This method is one of the possible approximations for the calculation of the cooling time of high carbon steels to 50 % martensite. This method was refined by T. Kasuya and N. Yurioka [7] using the CEH carbon equivalent of Harden :

$$T_{50} = (T_m \cdot T_b)^{0,5} = exp(5,3CE_H + 3,1CE_{III} - 2,03)$$
$$CE_{H} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{12} + \frac{Cr}{8} + \frac{Mo}{4} + \Delta H$$
$$C_{III} = C + \frac{Mn}{3,6} + \frac{Cu}{20} + \frac{Ni}{9} + \frac{Cr}{5} + \frac{Mo}{4} \qquad (1)$$
$$T_m = exp(10,6CE_H - 4,8)$$
$$T_b = exp(6,2CE_{III} - 0,74)$$

where

- T_{50} - the cooling time needed for 50 % martensite,
- T_m - the cooling time needed for 100 % martensite,
- T_b - the cooling time needed for 0 % martensite,
- CE_H - carbon equivalent of Harden,
- CE_{III} - carbon equivalent of Yurioka, which is used to estimate the strength of the weld metal.

It is important to note that this is for approximation purposes only, since CE_H can be interpreted up to 0.3% carbon content, above this limit the relationship between carbon equivalent and carbon content is no longer linear. Using this relationship, the critical cooling time for material 1.2741 results in 4 to 226 minutes, depending on the composition [7]. This large interval illustrates the relative accuracy of the calculation. Other widely used approximations, where the carbon equivalent of 1.2741 was outside the interpretation range, lead to similar results [8, 9].

1.3.2. The Béres method for high alloy steels

The best way to do this is to start from the CCT diagram of the material and weld it with so-called bainite preheating. In this case, the preheating temperature is the peak point of the bainite conversion curve and the preheating should be done slowly.

Based on this (Figure 1.) the decision was made to set the preheating temperature at 400–450 °C and the specimens were cooled down inside the oven [10].

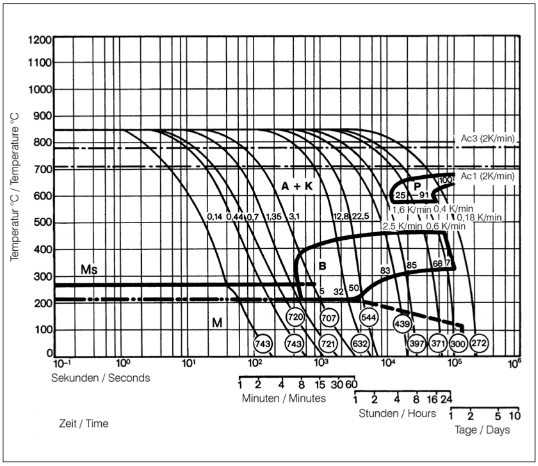

Figure 1. *Relevant part of the CCT diagram for tool steel 1.2741 (vertical axis: temperature (°C), horizontal axis: time (s) [10]*

1.4. The welding materials used

Four type of welding materials were used for the experiments, which differed significantly in their composition and processing properties. All wires were flux-cored and had a larger diameter than usual in robotic welding, since the typical wire diameter for robotic welding is 1.0 mm, the main properties of the used wired are listed in Table 1.

The development of the welding technology also required the inspection and revision of the technology window provided by the manufacturers.

Table 1. *Summary of welding materials*

Wire	Base	Alloying elements	Diameter
H1	Fe	Cr-Mo-C	1.2 mm
H2	Fe	Mo-Cr-C	1.2 mm
H3	Fe	Nb-Cr-C	1.6 mm
H4	Ni	Cr-Mo-W	1.6 mm

2. Welding experiments

To test the wires, 6 mm thick overlay welding was performed on a 100×100×250 mm specimen, twice for each. For the welding process a Yamaha EA1400 robot and an M21 type gas mixture were applied. Two samples of each were prepared. Meanwhile the processability was examined and later samples from these specimens for metallographic examination were machined..

2.1. Evaluation of processability

When evaluating processability, there are several aspects that are difficult to quantify. The features considered as important were evaluated using a scoring method established by me and summarized in tabular form. During the scoring process, the properties of the welding materials from one to four, with 1 being the worst and 4 being the best were rated. The properties and their evaluation criteria are as follows, the evaluation and comparison is summarized in **Table 2.**:

- Stability of the arc (I.): is it possible to find settings in the current-voltage technology-window specified by the manufacturer that provides a stable, well-focused and controllable arc?
- Spattering (II.): the rate of spattering with the most stable curve and the size of the droplets flying away. Fewer and smaller spattering is more beneficial.
- Shape of the bead (III.): the contact angle of the reinforcement of the weld, is there a risk of discontinuity during the welding of the next row, how smooth or wavy the surface will be after welding? Welds with wide and small contact angles are desirable.
- Productivity (IV.): time spent welding the specimen. The most productive procedure will be more favourable.
- Slag (V.): amount of slag formed after welding and its adhesion to the surface. Slim, easy to remove and meltable slag is more favourable.
- Fume (VI.): the wire that can be welded with less fume and soot formation is more favourable.

Table 2. *Comparison of the used wires*

Wire	I.	II.	III.	IV.	V.	VI.	Σ
H1	2	3	2	2	3	3	15
H2	1	2	3	3	4	3	15
H3	4	4	4	4	1	1	18
H4	4	3	4	3	4	2	20

2.2. Verification of the adequacy of the technology

The specimens were first subjected to a visual testing (VT), and after cooling, if possible, a regular penetration test (PT) was carried out. The specimens that did not pass these tests were no longer subjected to the micro-, macro-structure and hardness tests (HV). The results are summarized in **Table 3.**

Table 3. *Summary of the evaluation of the welded specimens; OK = acceptable, NO = not acceptable, – = not tested (the samples marks are the same as the wire used for its manufacturing process)*

Sample	VT	PT	Mikro	Makro	HV	Σ
H1	OK	OK	OK	OK	OK	OK
H2	NO	OK	–	–	–	NO
H3	–	–	OK	NO	OK	OK
H4	NO	NO	–	–	–	NO

In the case of H2 welding material, significant current fluctuations occurred during welding, which resulted in large fusion defects. The welds that were not affected by these phenomena haven't cracked.

In the case of welding material H4, the wire that worked properly during the setup produced a significant porosity of the weld metal. In the case of welding material H3, the slag layer was so thick and adherent that it was not possible to remove it, and large slag inclusions remained between the layers. In the H1 sample evenly distributed micro-slag inclusions can be observed on the cross-sections; however they do not significantly affect the functioning of the tool, their size and extent are acceptable.

3. Designing the robot cell

The following aspects had to be considered when designing possible robot cell variants:

- Reach: The robot must reach the work piece so that no singular arm position is formed during welding.

- Access: defined jointly by the robot and the welding torch. The internal wiring design is advantageous.
- Heat load: a key issue due to the high preheating temperature. A design that is more heat resistant or has a lower heat load is preferred.

Each robot cell was designed so that all of them have two workstations. This allows the preparation of the pieces to be welded at the same cell.

3.1. Extended reach robot

A large part of the robotic arm is located away from the welding area, so the radiant heat of the work piece is less stressful and the robot can also reach large tools. The disadvantage of this design is that the robot arm, for a general welding robot, is less universal, so if an existing task is eliminated, it will be harder to find a new one for this exact design. An external wired welding torch does not provide as good access as it can be with mounted on integrated wired robots (**Figure 2.**).

3.2. Robot with floor mounted track

The YR MH2010 has an extended work area, and is an internally wired welding robot, suitable for any welding task (**Figure 3.**). With the TSL 1000 floor mounted track, the robot's working space can be greatly increased, and the reach is improved not only in quantity but also in quality by making it easier to avoid singular arm positions.

3.3. Gantry robot

The biggest advantage of the Gantry robotic arm, which is mounted on a two-axis, upper travel track, is that its working area is very large, which means that it reaches every point of a large forging tool with a constant confidence (**Figure 4.**).

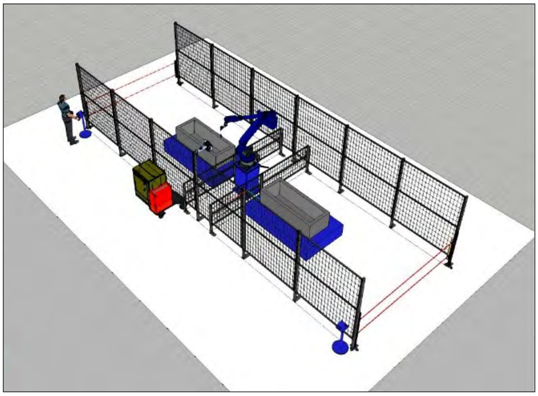

Figure 2. *Robot cell with extended reach robot*

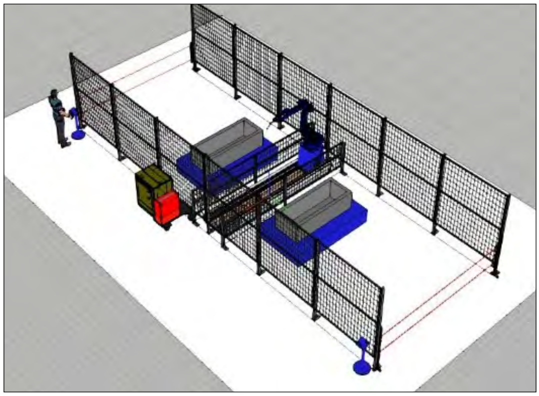

Figure 3. *Robot cell with floor mounted track*

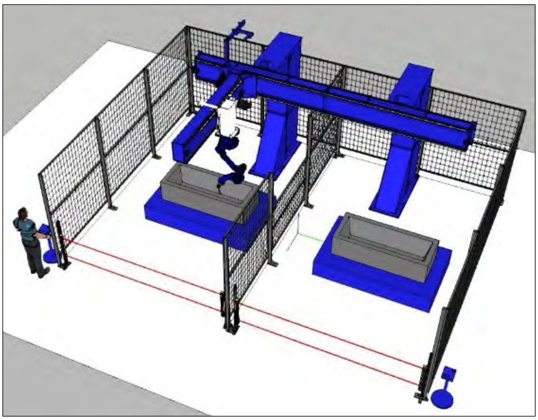

Figure 4. *Kobot cell with a two-axis upper travel track*

4. Summary

The optimal welding material can only be selected through field abrasion tests. The H1 welding material can be released without restrictions for these advanced tests. Despite the excellent workability of the H3 welding material, it is unlikely to work if slag inclusions cannot be satisfactorily eliminated in further experiments. Feed problems with H2 wire can be eliminated with a knurled roller and higher clamping force, further investigations are recommended. It could be also useful also repeating the tests with a new dose of H4 wire.

The design of the robot cell must be determined jointly with the customer, as operational conditions and financial capabilities may override other considerations. From the point of view of robot programming and access, the upper travel track cell with a Gantry robot is the best design, but also the heat load of the robot is the highest in this case; it is therefore necessary to consider what additional protection the equipment can withstand.

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