Friction Surfacing of Stainless Steel on Mild Steel with a Robot



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1 INTRODUCTION

Surfacing engineering is a very fast growing sector mainly because more and more the industry realises that using the right material at the right place results in substantial savings [1]. Surfacing can be applied to address a number of material problems such as corrosion, wear and fatigue. A wide range of surface improving techniques has been developed many of them being successfully applied in industry. Most of the coating techniques however, are related to problems such as porosity, slag inclusion or excessive dilution. Friction surfacing is a technique that improves the surface and is associated with very good metallurgical properties.

Friction surfacing is a solid-state metal deposition process, deducted from friction welding [2-4]. The process relies on the presence of relative motion between two parts while they are being pressed together under an applied axial force to generate the thermomechanical conditions for coating. The simplest relative motion is rotation of a consumable rod. In general the deposition is not carried out in order to join two workpieces together, but rather to create a layer on a workpiece in order to protect, restore or improve the properties of the substrate (Fig.1).



Fig.1: Illustration of the friction surfacing process [2].

In case of restoring, the substrate is damaged or worn-out. By means of friction surfacing the original thickness of the workpiece can be regained. In this case a friction surfacing layer is deposited on the damaged region.

The friction surfacing process has first been patented in 1941 by Klopstock and Neelands [5]. However, like many novel ideas, the technology lay dormant until the early 1960's. Until recently friction surfacing was only done on laboratory scale. New developments have recently made it possible to perform friction surfacing on commercial scale. Up to now the process has been limited to stationary applications in the flat welding position. This is mainly due to the required process forces, which implies in the use of large and rigid machine tools. At GKSS a investigation is started dealing with the possibilities and limitations of friction surfacing with a robot. The main advantage of using a robot is the freedom of 3D surfacing. A robot is less rigid, therefore research was carried out in order to obtain the process parameter window and to characterise and qualify the deposits.

This study is carried out as a final research project of the curriculum of the Department of Materials Science & Engineering at Delft University of Technology.

The outline of the thesis is as follows.

A general introduction and a review of the state of art of friction surfacing are given. In chapter 2 specific attention is given to the influence that the different process parameters have on the deposit.

In chapter 3 the experimental set-up for friction surfacing with the robot is described, the materials used in the study are listed and procedures of the testing the deposit are mentioned.

The results of the investigation are presented in chapter 4 and a discussion of the results compared with models regarding friction welding is given in chapter 5. Also is in this chapter a initiation given for modelling the friction surfacing process.

Finally, some concluding remarks are made and some recommendations for further research are given.

2 FRICTION SURFACING - REVIEW

2.1 The Friction Surfacing Process

Friction surfacing is comparable to friction welding where the rotating stud (also denominated "rod" in this study) is used as a consumable. In friction surfacing however, the stud material is used to produce a coating layer instead of joining workpieces. During friction surfacing no melting takes place and the temperature is kept near to the melting point of the stud material which is much lower than that reached by conventional coating methods [1]. Therefore, the process has a narrow heat affected zone (HAZ) and a negligible amount of diffusion between the materials at the interface. Moreover, porous defects are hardly observed. The layer is also characterised by a fine hot worked microstructure and has a strong bond with the substrate [2, 3, 6, 7]. Although high deposition rates can be achieved, the rod efficiency can be quite low because the plastified material is partly pushed up along the rod into the flash upset [7,9]. An eventual oxidation layer on the deposit, caused by the cooling down from high temperature in the air, can later be removed if necessary.



Fig.2: Principle of friction surfacing [7].

In friction surfacing deposition is achieved by bringing a rotating consumable rod in contact with a substrate. The relative movement combined with the applied axial force results in frictional heat and with adequate heat input the consumable rod plastifies. When sufficient plastification is achieved, the consumable rod is moved over the substrate creating a layer of deposited material (Fig.2).

It is possible to deposit a metal coating on a dissimilar metal substrate because solid adhesion is achieved by generating high contact stresses and intimate contact between the two metals [8]. For the one application it may be more important to deposit a thick enough layer in one pass while for another application a reduced HAZ might be more important. Depending on the purpose of the friction surfaced layer and a given material combination the most relevant friction surfacing parameters are:

- diameter of the consumable rod,
- coating speed,
- axial force, and
- rotational speed of the rod.

These parameters will be discussed in the following.

2.2 Process Parameters

A large number of investigations have dealt with the influence of the process parameters on friction surfacing. In Tables 1 and 2 the results of several investigations are given. The general tendencies of influence of the different process parameters on a number of specific characteristics are summarised in Table 3. Up till now, only more profound examinations have been done on influence of the rotational speed, as is described in Section 2.2.1 [7].

Table 1 clearly shows the complex nature of the reported results when comparing different reports on friction surfacing a stainless steel deposit on a mild steel substrate. To allow for comparison among different parameter sets the axial force is considered in relation to the rod diameter and given in MPa. The rotational speed is converted to a maximum relative speed at the circumference of the rod.

The numbers between brackets in all tables indicate the bibliographic reference, reporting the phenomenon. A dash (-) indicates that the values of the specific parameter were not mentioned.

| Material substrate | Mild steel | Mild steel | Mild steel | Mild steel | Mild steel | Mild steel | Mild steel |
|--|------------|-----------------|-----------------|-----------------|------------|------------|-----------------|
| Material rod | Stainless | Stainless steel | Stainless steel | Stainless steel | Stainless | Stainless | Stainless steel |
| | steel | | | | steel 304 | steel 316 | |
| Diameter rod [mm] | 25 | 20 | 25 | 12,7 | 19 | 19 | 25 |
| Rotational speed [rpm] | 550 | 300-2400 | 500-700 | 1500-3000 | 1400 | 1400 | 550 |
| Relative maximum speed of the rod [m/s] | 0,72 | 0,31 - 2,51 | 0,65 - 0,92 | 1-2 | 1,39 | 1,39 | 0,72 |
| Axial pressure [MPa] | 101,9 | 30 - 93 | 79,5 -101,9 | 5,5 - 19,4 | 10,6 | 10,6 | 101,9 |
| Welding velocity [mm/s] | 5,3 | 1 - 4 | 2 - 4 | 2,6 - 8,33 | 8,3 | 8,3 | 5 |
| Initiation period [s] | 3 | - | 0 - 4 | | 5 - 7 | 5 - 7 | - |
| Reference | [3] | [7] | [10] | [11] | [12] | [12] | [2] |

Table 1: Comparison of surfacing parameters for stainless steel deposition on a mild steel substrate.

In Table 2 the parameters for deposition of steels and Ni alloys on different substrate materials are given. Table 2 also shows a range of possible materials combinations.

The importance of the material combinations on surfacing parameters is highlighted by the results reported for depositing Stellite 6 on a stainless steel substrate and those for depositing tool steel on a mild steel substrate. In general the melting temperature of the rod is higher than that of the substrate.

Table 2: Comparison of surfacing parameters for steel and Ni alloy deposition on different substrates.

| Material substrate | Stainless | Aluminium | Aluminium | Mild steel | Mild steel | Mild steel | Alloy steel ¹ | Stainless | Al-4Cu | Mild steel |
|------------------------|-----------|------------|------------|-------------|-------------|-------------|--------------------------|------------|--------|------------|
| | steel | 5083 | 5083 | | | | | Steel | | |
| Material rod | Stainless | Stainless | Mild Steel | Inconel | Tool steel | Mill steel | Mild steel | Stellite 6 | Al-4Cu | Tool steel |
| | steel | steel 304 | 1020 | | | | | | | |
| Diameter rod [mm] | 10 | - | - | 12 | 12 | 25 | 25 | 20 | 25 | 19 |
| Rotational speed [rpm] | 3000 | 1500-3000 | 1500-3000 | 2500-3000 | 2500-3000 | 900-1500 | 800-1500 | 330 | 780 | 1400 |
| Relative maximum | 1,57 | - | - | 1,57 - 1,9 | 1,57 - 1,9 | 1,18 - 1,96 | 1,05 - 1,96 | 0,35 | 1,02 | 1,39 |
| speed of the rod [m/s] | | | | | | | | | | |
| Axial pressure [MPa] | 70 | 8,2 - 21,8 | 8,2 - 21,8 | 16,7 - 21,8 | 16,7 - 21,8 | 57,0 - 91,7 | 61,1-91,7 | 159 | 35 | 17 |
| Welding | 4 | 1,2 - 2,0 | 1,2 - 2,0 | 1,60 - 3,04 | 1,38 - 2,93 | 3 - 7 | 3 - 9 | 2,5 | 4 | 8,3 |
| velocity[mm/s] | | | | | | | | | | |
| Initiation period [s] | - | - | - | 5 | - | 0 - 4 | 0 - 3 | - | - | 3,5 |
| Reference | [13] | [14] | [14] | [8, 15] | [8, 15] | [10] | [10] | [2] | [2] | [16] |

¹ Alloy steel composition: 0,4%C; 1,5%Ni; 1,2%Cr; 0,25%Mo

In Table 1 and 2 is shown that there is a wide variety of parameter combinations and the relations between them still has to be examined carefully.

2.2.1 Effect of Surfacing Parameters on Process Behaviour

Table 3 shows the effect of major surfacing parameters on the characteristics of the deposit and the efficiency of the rod. The symbol \uparrow indicates an increase of the property mentioned and the symbol \downarrow indicates a decrease of this property. All results are reported for increasing the set parameter.

Table 3: The effect of surfacing parameters on the properties of the deposit and surfacing efficiency.

| | Increasing force | Increasing | Increasing |
|-----------------------|------------------|------------|------------------|
| | | traverse | rotational speed |
| Width | ↑ [7, 17] | - | ↓ [7, 17] |
| Thickness | ↓[7] | ↓ [17] | ↓[7] |
| HAZ | - | - | ↓ [7] |
| Contact area | - | - | ↓ [7] |
| Heat input | - | - | ↓[7] |
| Hardness | - | - | ↓[7] |
| Deposition efficiency | ↓[9] | - | ↓ [9] |

Experiments done by Shinoda et al. [7] and Fukumoto [17] show that with increasing force the width of the deposit increased and the thickness decreased. With increasing traverse speed the thickness of the deposit decreases [17].

Calorimetric measurements of the heat input during friction surfacing have been carried out by Shinoda et al. [7]. The influence of the rotational speed on the heat input in the rod and in the substrate has been investigated. It appears that the rotational speed hardly influences the total heat input generated by the process (see Fig.3). With increasing rotational speed, the coating material (i.e. consumable stud) absorbs more

of the total heat input with less energy being transferred to the substrate. In this way the heat input partition in the rod and the substrate can be controlled. When the thermal energy generated on the substrate increases, the HAZ becomes larger having a more pronounced effect on the resulting microstructure. The heat input generated in the substrate becomes relatively small when the rotational speed of the rod is high. This is because the relative contact area between the coating material and the substrate decreases with increasing rotational speed. Therefore, transfer of the frictional heat into the substrate decreases. As a result, with increasing rotational speed, the hardness in the HAZ and the deposit dimensions (i.e. thickness and width) decrease [7].



Fig.3: Distribution of heat input in the coating material and moving substrate [7].

The consumable rod will always produce a flash upset during friction surfacing and therefore the efficiency of the used rod will never be 100 %. Li and Shinoda [9] examined the influence of rotational speed and friction pressure on the deposition efficiency. The efficiency of friction surfacing is measured as the ratio of the metal deposited to the total consumed metal. The influence of rotational speed and friction pressure on the efficiency is shown in Fig.4. The lower the rotational speed and the friction pressure the better the deposition efficiency [9].



Fig.4: Influence of friction surfacing parameters (friction pressure and rotational speed of the rod) on the deposition efficiency in air [9].

2.3 Process Characteristics

An important physical property in regard to friction surfacing is the thermal conductivity of the metal used. It appears that materials with a high thermal conductivity do not allow a heated layer to form during friction surfacing. Batchelor [11] mentions that, in contrast with stainless steel 304, AA6061 and brass do not show any adhesion with the mild steel substrate. The heat conductivity of AA6061 and brass is about 10 times the heat conductivity of stainless steel. Therefore to create a aluminum or brass deposit on mild steel the rotational speed should be increased substantial or the contact stress should be raised.

Another problem arising with the choice of the deposit material is that it should have a high friction characteristic. Stainless steel is associated with a high friction coefficient, whereas brass is effective bearing material. In the research of Barchelor [11], brass did not form a deposit at all. Aluminium, which is tending to frictional seizure in sliding wear, showed limited signs of frictional deposition, which were suppressed by the lower temperatures prevailing [11].

Friction surfacing can be divided in two periods: the initial dynamic contact and the traverse motion [8, 10].

During the initial dynamic contact period the rod and the substrate make contact with each other. In this period the rotation of the consumable, while under axial force, scours the oxide layer from both the rod and the substrate contact faces and the temperature at the interface increases. The initial contact will remain for several seconds until a plastified layer is formed. During this time slight dilution of the substrate and material of the consumable can be observed [10].

In the following period (i.e. traverse motion) the consumable is driven over the substrate. During this period the rigid rod is not in contact with the substrate. Only the plastified layer, which has lower mechanical strength, is in contact with the substrate resulting in a less effective scouring action. Therefore the dilution of the rod material in the substrate is negligible (i.e. low dilution).



Fig.5: Sketch of the flowlines in horizontal section through deposit produced by friction surfacing and surface image of experimental deposit [9].

Fig.5 shows the flowlines in a horizontal section through a deposition layer produced by friction surfacing. The surface appearance of the deposit is shown in Fig.5b. The

orientation of the flowlines differs at the starting point, during surfacing and at the end of the deposit. In the starting point the flowline pattern is symmetric. At this point the rod has been rotating for a while without moving along the substrate. At the middle part (i.e. condition during surfacing) the rod is driven along the substrate with a constant traverse speed while rotating. The relative velocity of the rod surface is different at the advanced and retreated side because a uniform velocity component (coating speed) is added to the rotational speed. Fig.6 illustrates the superposition of the rotational speed of the rod and the coating speed.



Fig.6: Schematic illustration of the shift in nil velocity axis from: a) starting position to b) condition during surfacing and c) asymmetry in friction surfacing deposition mechanism [9].

Fig.6a shows the velocity distribution of a rod, which has only a rotational speed and no traverse speed. Fig.6b presents the velocity distribution when the rotational speed is combined with the traverse (i.e. coating) velocity as a result of driving the rotating rod along the substrate. The place where the relative velocity is zero has moved from the centre to the side where the rotation speed has the opposite direction to the travelling speed of the rod on the substrate. In the third picture (Fig.6c) the flowlines at the lag side, or retreating side, are closer to each other than the lines at the fast side of the rod, also called advancing side. Consequently, the centre line becomes offset from its original position and a retreating and an advancing side are made visible in the flowline pattern.

Fig.1 and Fig.6 show a friction surfacing phenomena, the 'deposit lag'. The 'deposit lag' is the retarded movement of the deposit in relation to the rod position. In Fig.6c the deposit is illustrated by the circle number 1 and the actual position of the rod by the circle number 2. The drag of the deposition is the difference between these two circles, which is shown as Δt .

It must be emphasised that Δt is very small (i.e. 0,001 mm), since the transverse speed of the substrate is relatively slow (i.e. 1 mm/s), specially compared to the rotational speed of the rod which can exceed 800 rev/min. A small Δt is important to

ensure a continuity of deposition with constant rotational speed of the rod and the traverse speed of the substrate [9]. According to Thomas [10], scouring action is needed to achieve a good bond. The scouring during the surfacing stage is not produced by the contact between the rod and the surface, but rather by the contact between the substrate and the plastified layer derived from the consumable rod. The rod and the substrate are separated by the deposit and therefore do not touch during friction surfacing (Fig.7).



Traverse sliding of substrate

Fig.7: Principle of friction surfacing and 'deposit lag' phenomenon [9].

The deposition area can be divided into four zones (A, B, C and D) and two positions (E and F) as is shown in Fig.6c. This classification is made on account of the local relative velocity of the rod and the deposited metal. In C, at the retreating side, the shear stress is greater than in the advancing side (zone B), because the deposition metal is pushing against the already existing deposition. In zone A, the frictional heat is generated. The relative velocity in zone C is lower than in zone B, and lowest at position F. Therefore, the temperature is lowest at position F, while highest at position E. In zone D the rotational velocity is hardly effected by the velocity of the substrate since their orientation is perpendicular [9].

The frictional heat is produced in zone A, where the consumable rod is on the deposit rotating and causing frictional heat. Apart from plastifying the rod the friction heat also retards cooling of the deposited layer minimising quench related defects [9]. The period of time in which the axial force is being applied on the surface is called action time. The action time is shorter at the sides than in the middle of the deposition, since the rod only brushes the surface layer at the sides, while in the centre the full diameter of the rod is pressing the surface during its passing. By this the period of heat input and axial pressure is dependent on the transversal position in the deposit. While rotating the rod, the plastified material in the deposit lag will be continuously exposed to the atmosphere. This also may introduce oxygen in the surfacing layer [10]. Thomas [10] found that the oxygen layer of the substrate could interfere with the deposition and reduce the bonding between the two materials.

2.4 Characteristics of the Deposited Layer

The characteristics of the friction coating layer are dependent on the combination of the parameters as mentioned before.

For a constant rotational speed, higher frictional pressure results in a wider spectrum of possible coating speeds for defect-free deposits (Fig.8). This can be explained by the fact that, for a constant rotational speed, lower axial forces generate a restricted amount of plastified rod material, limiting therefore the travelling speed to achieve satisfactory deposit quality.





In the following the influence of the process parameters on the layer dimensions, hardness and microstructure are discussed in more detail.

2.4.1 Layer Dimensions

As mentioned in Section 2.2.1, for a given material combination the width and thickness of the deposited layer are influenced by the primary surfacing variables, i.e. the rotational speed of the rod, the diameter of the consumable rod, the axial force and the coating speed.

The width of the fully bonded zone is usually about 1 to 3 mm smaller than the diameter of the consumable [2]. In other words, the edges of the layer always show lack of bonding. The surfacing material is highly plastified at the outer sides of the rod because the highest speeds are reached at this position. The flash upset (Fig.1) leads to a non-uniform pressure distribution at the outer diameters followed by the lack of bonding in this area [2]. A reduced action time by the rod on the edges of the surface is assumed also to contribute to the lack of bonding of the sides of the deposited layer [2].



Fig.9: Effect of pressure and rotational speed on the width and thickness of the deposit [7].

Fig.9 presents the frictional pressures as a function of the rotational speed for several values of axial pressure. The illustration indicates the influence of the axial friction pressure and rotation speed on width and thickness of the coating layer. When the axial (frictional) pressure increases, the thickness will decrease and the width of the coating layer will increase [7].

The heat input is measured according to the calorimeter method [7]. Increasing the rotational speed affects the total heat input barely (Fig.3). The division of the heat input over the rod and the substrate does change substantially with increasing rotational speed. At higher speeds, relatively more heat is absorbed in the rod while a decrease of heat input into the substrate is observed [7]. These changes in heat distribution result in an increase in the flash upset and therefore the deposition efficiency of the rod decreases [9].

As stated before, the thickness of the deposited layer depends on the material of the consumable stud. A material with a high resistance to plastic deformation requires higher temperatures to produce a deposit and the layer is consequently thinner [2]. In case of Ni-based alloys for instance, deposition layers of about 0,5mm thickness can be achieved. For austenitic stainless steels and carbon steels layers of up to 3 mm have been reported in the literature [2]. Deposition layers of up to 6 mm can be realised with aluminum alloys, even though the applied axial pressure is much lower than those required by Ni-based alloys or conventional steels, as mentioned above [2].

2.4.2 Hardness

Most of the applications of friction surfacing require a high hardness of the deposit. The distribution of the hardness across a mild steel substrate and a stainless steel coating material, as a function of the rotational speed, has been determined by Shinoda et al.[7]. The specimens have been produced with a constant friction pressure and a variable rotational speed. The results are shown in Fig.10.

Fig.10: Hardness distribution of coatings at different rotational speeds (in rev min⁻¹) [7].

During friction welding and friction surfacing the increased local temperature causes recrystallisation, which can be expressed in terms of hardness. It can be seen that the hardness of the coating is higher compared to the hardness of the substrate and that a lower rotational speed results in harder coatings. Fig.10 also shows that the highest hardness values have been measured in the middle of the coating layer. Once deposited the surface of the coating layer cools down slowly because of the continuous heat input of the rod. Closer to the interface the coating layer experiences higher cooling rates due the heat sink effect caused by the substrate which should result in higher hardness values.

The bulk of the substrate has its original low hardness since between the interface layer and the bulk substrate a high temperature gradient caused by a high heat transfer in the substrate. The hardness increases when the measurement points are closer to the interface. This indicates that the substrate is hardened at the interface.

2.4.3 Microstructure

A typical microstructure of a stainless steel coating layer, with fine carbide particles is presented by Shinoda et al. [7] in Fig.11. The matrix shows ultra fine dispersed carbide particles that are uniformly distributed throughout the coating. The finest microstructure is realised by low rotation speed in the order of about 600 rev/min The rod has a diameter of 20 mm. The coating material was fed towards the rotating interface while undergoing hot working at the interface with severe plastic deformation at high strain rate. The temperature of the plastified zone during this process is just below the material's melting point. This results in recrystallisation and refinement of the matrix. The fine carbide particles are uniformly distributed throughout the coating layer. The refinement in combination with the spiral movement during the processing of the consumable rod brings out the fine uniform distributed structure.

Fig.11: Micrograph of a stainless steel coating layer deposited by friction surfacing [7].

2.5 Multilayer friction surfacing

The maximum diameter of the consumable rods is limited by the power of the machines used. These restrictions are limiting the surface layer in width. To overcome these restrictions, experiments are carried out on multilayer friction surfacing [7]. A lot of defects occur in the bonding zone between the layers during multilayer fictional surfacing, therefore a machining operation has to be carried out to remove the cold laps realising a defined edge profile. In order to machine the edges optimal by the influence of the rotational direction of the rod and the different shapes of edges on the coating layer were investigated by Shinoda [7].

The influence of the rotational direction of the rod is related to the side on which the edge is and on the traverse direction (Fig.12).

The influence of the direction of rotation of the rod on flow patterns is shown in Fig.13. The plastic flowlines are the result of the difference in etching between the consumable rod material and a tracer wire inserted in the rod. Since deposition takes place at the front of the rod (Fig.7) the flow patterns show the state of the flow in this area. As shown in Fig.13 the deposition at the front of the rod gives a regular easy flow pattern when the rod is rotating counterclockwise. The rod is sliding of the edge at the front and therefore a low shear stress is experienced. When the rotational direction is clockwise, the front of the rod is pushing against the edge and a high shear stress is obtained, causing an irregular turbulent-like flow pattern.

a clockwise rotation; *b* counterclockwise rotation Fig.13: Patterns of plastic flow on the cross-section of a coating layer [7].

On the other hand, the shape of the edge can alter during friction surfacing because of the direction of the rotation of the rod as is illustrated in Fig.14. This can also provide or intensify the presence of shear stress resulting in a more irregular flow pattern. As mentioned before, the shape of the edge significantly effects the weld structure. The presence of local incomplete bonding at both sides of the weld, also called 'cold laps', is inevitable as is mentioned in chapter 2.4.1.

Fig.14: Effect of rotational direction of consumable rod on distortion of preceding edge caused by the rotation direction a) clockwise and b) anticlockwise of the rod: broken lines denote the initial profile of the substrate [7].

TWI investigated the effects of the groove shape on the bonding integrity in friction surfacing [7]. Four typical edge preparations were used: right angle stair (90°), inward bevelling (IN45°), outward bevelling (OUT45°) and round root (R). The results of the experiments indicate that the round root edge preparation is able to match the plastic flow of the consumable rod metal in the best way (Fig.15). The outward bevelled edge is almost matching up with the round root edge. The right angle stair edge shows a clear mismatch and using the inward bevelled edge a sound bounding can only be attained at great risk of potential bonding defects in the corner of the preceding edge.

Fig.15: Relationship of cross-sectional area of coating to overlapping distance with clockwise rotation [7].

TWI reports as well that the overlapping distance (OLPD) between one layer and the next one has also a significant influence on the bonding integrity and the cross sectional area of the coating layer. The cross sectional area increases with the increase of the overlap. When examining the cold laps, it was found that the bonding integrity was unacceptable with increasing overlapping distance (Fig.15). To find an explanation for this problem Shinoda et al. [7] divided the multilayer friction surfacing weld into two parts i.e. an upper and a lower part. Because of the difference in height, the upper part of the friction weld will undergo sever axial pressure and therefore extensive deformation will take place in this area [7]. The lower part of the weld experiences a lack of pressure, which can cause lack of bonding. When the rotation of the consumable rod is clockwise (this is pushing against the edge with the front of the rod), the corner in the edge most likely will be filled, nevertheless the bonding may be poor. When the rotational direction is counterclockwise, besides incomplete bonding also filling defects may occur in the corner of the edge. As a result, Shinoda et al. [7] report that zero overlapping distance and clockwise rotation give the best filling and bonding results.

2.6 Underwater friction surfacing

Investigating the influence of the wet environment on friction surfacing, Li and Shinoda [9] carried out a number of experiments. They used a water basin with a fixed temperature, as is illustrated in Fig.16, and compared the results to experiments in air [9]. The temperature of the water was fixed at 20 °C and at 100 °C. During these experiments low carbon steel was used as a substrate and martensitic stainless steel (1% C and 17% Cr) was used as coating metal.

Fig.16: Schematic illustration of underwater friction surfacing [9].

Fig.17 shows a cross-section and the surface of the deposit. The layers processed underwater show less oxide and the surface has uniform ripples. In order to get the same temperature at the plastification and deposition area as in air, a higher heat input is needed. This is realised by raising the axial force. A side effect is that the deposit is thinner and wider than the deposit made in the air. Fig.17 also shows a good adhesion of the layer to the substrate and a narrow HAZ.

Fig.17: Cross-sectional and surface appearance of deposits produced in air and under water [9].

Usually the efficiency is significantly influenced by the process parameters (chapter 2.4).

Li and Shinoda [9] report that in underwater friction surfacing the efficiency remains almost constant at various rotational speeds, while it is always lower in air (Fig.18). The cooling effect of the water probably limits the consumable upset volume, resulting in a thinner deposit layer. The higher friction pressure that is required for underwater friction surfacing (compared to surfacing in the air) is necessary to compensate for the higher heat loss caused by the water.

Fig.18: Deposition efficiency of friction surfacing in air and under water at various rod speeds: 75 MPa frictional loading [9].

In order to compare the hardness of deposits at different cooling rates, experiments were carried out in the air, in water with a temperature of 20 °C and in boiling water. The results are shown in Fig.19 and Fig.20. The hardness of the coating layer, made in air, shows a decline to the surface of the layer (Fig.19). The cooling rate at the interface of the coating layer and the substrate is very high because of a relatively high heat flow caused by the size of substrate. The cooling rate at the surface is much lower, since the heat flow through the rod is limited. During the underwater test where the water is 20 °C the substrate still has a high cooling rate and now also the water is quenching, which together causes a more uniform hardness. In Fig.20 the difference between friction surfacing in warm and cold water is shown. Both the test results show uniform hardness though the experiments carried out in the boiling water have a slightly lower hardness.

The quenching in both warm and cold water did make the metal harder and uniform hardened. Even though quenching takes place, defects such as cracks did not occur.

Fig.20: Hardness distribution in deposits under water at 20°C and in hot water (near boiling) [9]. H = hot; R,C,L = right, centre, left

As a result of severe plastic deformation during friction surfacing, a refined and uniform microstructure can be found in the deposit metal, even though the carbides in the consumable rod were coarse. The carbides in the underwater friction surfacing process are even finer than in the dry deposited coating (Fig.21). This is because in underwater conditions the frictional pressure and the cooling rate are higher than they are in dry friction surfacing.

2.7 Friction Surfacing Equipment

There are three basic set-ups for friction surfacing: modified machine tools, custom made friction surfacing and robots.

At the beginning standard machine tools (i.e. milling machines) and modified continuous drive friction welding machines have been used to develop the process [2, 8]. During further development, it appeared that an increase of the surfacing capacity was necessary, to perform longer deposition runs with larger diameter rods. The equipment can generate a high axial force, resulting into forces exceeding 50 kN, on the work piece and eventually on the working table. This working table should be able to withstand this force. In this type of machines the working table with the work piece moves underneath the consumable rod. The longitudinal velocity of the table is variable (0,5 mm/s up to 17 mm/s) and should be set in advance depending on the primary surface parameters, like the diameter of the consumable rod, the rotational speed, the axial force, the substrate transverse speed and the type of materials being used.

At the moment there is only one company (Frictec) performing friction surfacing on a commercial basis. Special equipment has been developed and purposely built for friction surfacing applications. The equipment has the possibility to rotate the rod which several speeds and to apply force with the rod on the substrate [18]. The substrate is, while surfacing, moved along the rod as is shown in Fig.7.

At GKSS robots are used for friction surfacing. The Tricept 600 (Fig.22) has been selected for preliminary experiments with friction surfacing. This system is available on the market since 1994 and so far approximately 130 units were sold world-wide The Tricept 600 system has a payload of 100kg and a force capacity in the vertical axis of 15.000N. Moreover, this system can apply up to 3500N in the coating direction, which increases resistance against transverse forces. The tripod design lends high stiffness to the system allowing the application of the FSW process to thicker and higher strength alloys. In this case the robot moves the rotating rod along the workpiece.

Fig.22: Tricept robot, used for friction welding and friction surfacing experiment.

2.8 Applications

Friction surfacing is a solid state coating process, which is increasingly competitive with other coating techniques [1, 2]. As regard to the material aspects it is well established that the friction surfacing technique is able to join many similar and dissimilar metal combinations. Also friction surfacing has a wide range of combinations of similar and dissimilar metals to use now for coating purposes [1].

Most of the applications of friction surfacing in general are protection against hard environmental object, erosion, corrosion or other pernicious environmental attacks and repairs of worn out parts [1, 2, 16].

Applications, where it has already proven its success, are hardfacing on cutting edges and on agricultural tools. Protecting and repairing of turbine blades, shear blades, disk brakes, rail bars, machine tipped tools and press tool dies by friction welding are also possible applications [2, 12].

Li and Shinoda demonstrated the possibility to use friction surfacing instead of sintering for the cutting edges of knives and the results are very good [19].

Research is still carried out in the field of thin layer heavily cold-rolled friction surfacing. Other promising work is done with hermetic sealing of containers especially for heat sensitive contents.

3 EXPERIMENTAL PROCEDURE, MATERALS AND EQUIPMENT

In this research project, experiments were carried out by means of a robot, which was recently installed at GKSS. In general, a robot has a low stiffness compared to the rigid milling machines or specially built equipment used so far. In this study the possibilities and limitations of using a robot for friction surfacing are investigated. The results are compared with the results obtained with fixed machinery as mentioned in the literature.

As stated previously the main advantage of using a robot for friction surfacing is the fact that it could be applied to all kind of surface shapes and components.

3.1 Plan of testing

A large number of experiments were carried out with different sets of process variables. In order to make it possible to compare with previous experiments reported in the literature, a similar material combination was used.

Three parameters were varied:

- the rotational speed, varied around ca. 1800 rpm, 2400 rpm and 3000 rpm;
- the axial force was applied on the rod with a maximum of 8,4 kN;
- the maximum traverse speed, i.e. the velocity with which the rod moved over the surface was 630 mm/min.

The initiation time and force were kept constant.

The deposit layers were first visually examined. The width and the thickness were measured and topview photographs were taken. The coated plates were cut, ground, polished and etched in order to investigate the bond quality, microstructure and the HAZ.

Further examining was carried out on a microscope. The bonding percentage and side lap percentage (area at the edge where no bonding occurs) were measured. Because there are also areas with voids in the bonding, the sum of the percentages of the bonding and the side lap might be smaller than100 % together.

After microscopic examination the polished specimens were used for hardness testing. For the bending tests longer surfacing layers were specially made. The coating layers were tested by bending them in longitudinal direction. With SEM an element analysis was obtained to give an impression of the dilution of the deposit and the substrate material at the interface. The deposition efficiency of the friction surfacing rods was calculated after the surfacing experiments. The efficiency is important in connection with the frequency of changing the rods during friction surfacing. To decide on the efficiency of the surfacing rods, the length and weight were measured before and after surfacing. The relation between the amount of material plastified (change in length) and the change in weight gives the efficiency of the rod used.

In the following sections the used equipment and the experimental set-up for friction surfacing with the robot is described, the materials used in the study are listed and the procedures of the testing the deposit are defined.

3.2 Equipment for friction surfacing

The advantage of a robot over fixed machinery is that the arm of the robot applies the rotational speed of the rod, the axial force and the welding velocity, while the substrate is fixed. Also the arm of the robot can make 3D movements. These advantages make it possible to do friction surfacing on almost any surface.

For the experiments at GKSS the robot TRICEPT 600 was used (Fig.22 and Fig.23). This robot has a Comau C3G control mechanism. The positioning of the rod is done by the use of 6 axes and has an accuracy of about 200 μ m. The repositioning has an accuracy of about 200 μ m. The reposition of 0,5 G and its maximum velocity is 40 m/min. It is possible to apply a maximum force of 15 kN in vertical direction and 3,5 kN in horizontal direction with the robot. The robot is equipped with a load cell between the end effector and the spindle attached to it for friction surfacing. A closed loop force feedback is implemented in the control, which allowed to move the robot along a programmed path with a given downward force. This made it possible to check the actual applied force afterwards.

Fig.23: Friction surfacing with a TRICEP 600 robot.

At the end of the robot arm the spindle was fixed for rotating the rods. The spindle was able rotate the stud with a maximum rotational speed of 3000 revolutions per minute. On lower speeds like 1500 rpm, the spindle did not have enough power to continue rotating when starting with applying axial force. The resistance during the initial force became too big for the motor of the spindle. Therefore rotational speeds of 1800, 2400 and 3000 rpm were chosen for the tests.

3.2.1 Surfacing set-up

As mentioned before, the robot TRICEPT 600 was used for all the surfacing examinations. A steel table was used to support the substrates while surfacing. This table has the possibility to fix the specimens on it with screws and clamping equipment. On this table a guiding system was fixed because the capabilities of the robot and the spindle for this process were unclear. This guiding system consisted of a steel plate, fixed on the welding table, where the spindle was pressed against while moving over the substrate. The substrate was fixed on the table along the guiding system (Fig.24). The first surfacing experiments showed a very unstable behaviour despite the guiding system. However, with other settings of process parameter the system became stable. In order to keep the system as steady as possible the guiding system was used in all the experiments.

Fig.24: Set-up of the substrate.

A computer was connected to the robot for data acquisition of the applied force. It was found that due to a programming error in the control software the applied force during the test was about 0,6 times the set value. Since this system error was constant and reproducible it was accepted and the correct force values were obtained by taking this error into account.

3.2.2 Parameter settings

The main parameters were rotational speed, traverse speed (i.e. welding speed) and axial force. These parameters were changed for the different series of experiments. The initiation time, i.e. the time where the stud is having frictional contact with the substrate in stationary condition, was set on 4 seconds. The initiation force, applied during the initiation time was 1900 N. Most of the tests were performed with a rod diameter of 10 mm and a rotational speed of 3000 rpm. This resulted in matrices with

variable force and traverse speed. In these schedules pictures were inserted which give an impression about for example layer thickness and width, HAZ, bonding and weld appearance. Also experimental data are presented in these schedules to give a better overview of the results.

3.3 Materials and properties

The consumable rods were made out of stainless steel (1.4571). The initial rods are 100 mm long, for the bending tests longer welds are made and therefore rods with a length of 120 mm are used. The geometry of the studs is as shown in Fig.25.

Fig.25: Geometry of the rods used for the friction surfacing experiments.

To have an evenly distributed axial pressure on the stud a shoulder was provided in the design of the rods. The other advantage of the shoulder is that the length of the rod could be measured precisely which made programming the robot easier, resulting in comparable surfacing layers. Preliminary experiments were carried out with rods of 15 mm in diameter. However, due to power limitations of the spindle, the following experiments were mainly carried out with 10 mm rods.

For the substrate a mild steel was chosen (120 mm x 300 mm x 13,5 mm).

The chemical composition and the mechanical properties of the rod and the substrate are given in Table 4 and Table 5.

| Table 4 | 4: | The | chemical | composition | of | the | materials | used | for | the | friction | surfacing |
|---------|-----|------|----------|-------------|----|-----|-----------|------|-----|-----|----------|-----------|
| experin | ner | nts. | | - | | | | | | | | - |

| | С | Si | S | Р | Mn | Cr | Ni | Мо | Ti | Cu | AI | V | Fe |
|-----------|-------|-------|--------|-------|------|-------|-------|-------|------------------|-------|-------|-------|------|
| | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] | [%w] |
| Rod [21] | <0,08 | 1,0 | 0,030 | 0,045 | 2,0 | 16,5- | 10,5- | 2-2,5 | <u><</u> 0,70 | - | - | - | ±70 |
| (1.4571) | | | | | | 18,5 | 13,5 | | | | | | |
| Substrate | 0,118 | 0,269 | <0,001 | 0,024 | 1,41 | 0,085 | 0,081 | 0,022 | <0,001 | 0,056 | 0,041 | 0,031 | 97,8 |

| | Rod | | Substrate |
|---|---------------------|--------|-----------|
| | Specified [21] | Tested | Tested |
| | | values | values |
| Material code | 1. 4571 | | |
| Hardness HB30 | ≤ 215 | 215 | |
| 0,2 %Yield stress (N/mm ²) | ≥200 | 693 | 485 |
| Tensile strength (N/mm ²) | 500 – 700 | 770 | 595 |
| Elongation after fracture % ($L_0 = 5 d_0$) | ≥40/30 (transverse) | 19,5 | 28,6 |
| Impact value (ISO-V) J | ≥100/60 | - | 168/115 |

Table 5: Properties of the materials experimentally determined and according to material specifications, used for the friction surfacing experiments.

3.3.1 Tensile testing

The tensile strength of the substrate material and the rod material was determined by tensile testing. All tensile tests were performed on round specimens by means of a Zwick tensile test machine. Elongation was measured by placing a strain gauge on the L_0 marks made on the specimens before testing.

Three tensile tests for stainless rod material were carried out with tensile specimens M8, diameter 5 mm and $L_0 = 25$ mm. The velocity of the machine was set on 0,50 mm/min. The starting force was every time set to zero. The strain gauge, with a maximum reach of 50 mm, was placed on the specimens by placing the clamps on the L_0 marks as exact as possible. The maximum force expected was 13 kN, the maximum force applied was 16,84 kN. This resembles a tensile strength of 775 MPa for the stainless steel rod specimens (Table 5). The expected ΔL was 8 mm. Therefore the maximum registered length was set on 20 mm. While testing the first two specimens, ΔL was found to be around 5 mm. Therefore during the last test the maximum registered length was set on 10 mm. The measured strain was 19,5% (Table 5), which is much lower than the expected strain of approximately 40%. An explanation for this deviation can be the fact that the rod material probably is prestrained.

The specimens of the substrate material (mild steel) had a standard geometry M12 with a diameter of 8 mm. L_0 was set at 40 mm and the velocity was 1mm/min. The clamping of the strain gauge was placed on the scratch marks for L_0 and then set on 40 mm (+/- 0,02 mm) on the display of the Zwick machine. The first specimen still had the strain gauge with maximum L = 50 mm. As $L_0 = 40$ mm and the expected ΔL is 13,5 mm, the strain gauge could not register all the data. After changing the strain gauge with a higher maximum reach, the next four specimens were tested. The maximum elongation was 28,6% and the maximum tensile strength was 595 MPa (Table 5). With specimen FS-MS-02 the necking was very close to one of the clamps measuring the elongation and therefore part of the elongation happens outside the measured area.

3.3.2 Charpy testing

Since the properties of the base material were not fully known, charpy tests were performed. The results are given in Table 5. In Fig. 26 the average results of the testing are given in a chart. The procedure followed during the testing is as follows:

All charpy specimens were checked on their dimensions to see if they were within the specified tolerance. Per temperature 5 specimens were tested. The test temperatures were - 40°C, - 20°C, - 10°C, 0°C and 20°C. A specific procedure to ensure the exact temperature was as follows.

While cooling 10 specimens to $T = -40^{\circ}$ C, five specimens were tested at room temperature. When the specimens were at $T = -40^{\circ}$ C, five of the specimens were tested. Then five new specimens were added to the cooling system and the temperature was raised to -20° C. When the system was at the right temperature, the specimens that were already in the cooling system at $T = -40^{\circ}$ C were tested. After the test the last five specimens were added. Then the temperature was raised to -10° C. At this temperature tests were carried out with the five specimens added to the cooling system at $T = -20^{\circ}$ C. Then the system temperature was raised again and when the specimens had a temperature of 0°C, the last five charpy tests were carried out.

The temperature of the specimens was determined by measuring the temperature in the centre of a dummy specimen. By adding the new specimens at too low temperature the problem of temperature difference in the dummy and the new specimens was avoided.

Fig.26: Average Charpy energy of the substrate material at different temperatures.

The machine used for the testing was a MFL Systeme, D6800 Mannheim, type PSW300. An initial energy of 300 J was applied on the specimens. The retained energy was deducted from the initial energy. This gave the energy used for the impact on the specimen.

The specimens were placed against the vertical holder and the position of the charpy notch was defined with the therefore designed tool on the equipment.

After the tests the specimens were immersed in a glass with alcohol in order to avoid corrosion while bringing the specimen to room temperature. Then the specimens were dried and sprayed with a coating spray.

3.4 Deposit examination

After surfacing the coating layers were examined. To decide on the new set of process parameters, the shape and visual bonding of the deposit was directly evaluated. At the start of testing the surfacing was in series of dots. Then layers were created, which did not stick on the substrate. Eventually layers, with a good surface finish and a good adhesion to the substrate were produced. These deposits were further examined with the microscope and hardness. Furthermore bending tests were carried out. Other tests like through-thickness tensile tests and pushing a wig under the cold lap were considered [3, 16, 22]. The technique used in the literature for tensile testing is one that fixes a stud on the deposit with friction stud welding in order to be able to make tensile specimens. The friction welding of the stud on the deposit could give a heat treatment to the specimen and therefore it was considered to be an unreliable testing method. The wig under the cold lap could give an impression of brittleness of the cold lap instead of the bonding qualities of the deposited layer.

The results of the measurements are depicted in force-traverse speed matrices.

3.4.1 Visual and optical analyses of the specimens

After friction surfacing the deposits were visually examined. In this way a qualitative impression of the coating appearance and bonding was obtained. Specific attention was given to the shape of the deposits. In preliminary experiments the parameters were adjusted in order to avoid a discontinuous layer, i.e. a set of dots, and to establish a good joining of the deposit on the substrate. The initial experiments resulted in non-sticking layers. By adjusting the parameters good deposits were produced

Then the samples were cut into specimens for optical analysis with the microscope. The specimens were cut with a band saw and a disk cutter. The cuts were made transversal at about 15 mm from the end of the deposit. The end part was used for transversal examination. The first 35 mm was used to get information on the longitudinal qualities of the deposition layer by cutting it in the middle of the deposit. Then the specimens were moulded with Demotec 30.

After this the specimens were ground on an Abraplan for 20 - 40 seconds with water and a grit size of 100 μ - 150 μ . Then the specimens were polished on an Abrapol of 6 μ and 3 μ for 6 minutes with a rotational speed of 150 rpm and a force of about 20 N. At 1 μ polishing was performed for about 6 minutes at a force of about 15 N and again with 150 rpm.

After polishing at 1 μ the mild steel specimens were etched with Nital 2% (HNO₃ and alcohol). By means of optical light microscopy the HAZ and the bonding area were revealed. The microscope used was a Reichert MEF3.

With the macrograph pictures, taken with the light microscope, a percentage of bonding is calculated. The procedure to determine this percentage of bonding was as follows. With the microscope and pictures of the macrostructures again the bonding quality was examined. The bonding quality was registered on the macrograph pictures.

3.4.2 Efficiency of the rod

Beside the weld quality also the rod efficiency was examined. The efficiency of the rod is defined by the relation between the material used for the deposit and the total amount of material used. In Fig. 27 the different stadiums of the flash-up were shown. In this picture is also shown that when the flash-up has grown against the shoulder of the stud, a second flash-up starts to grow.

Fig.27: Different stadiums of the flash-up, including the development of a double flashup.

In order to find a relation between the efficiency and the parameters, the weight and the length of every rod was measured. After surfacing the rods were weighed and measured again. In this way a difference in length and weight was calculated. The loss of weight is the weight of the material used for the deposit. The loss of weight is corresponding with the length that should have disappeared if there was no flash-up. The theoretically used length was divided by the actually used length and multiplied by 100. This gives a percentage of efficiency of the rods. The results are put in a matrix to compare the relation of the efficiency to the process parameters.

3.4.3 Hardness testing

Microhardness measurements were carried out on a subset of the experiments. The cross sectional cut specimens, produced with a rotational speed of 3000 rpm, an axial force between 3,6 kN and 8 kN and the velocity, varied between 330 - 630 m/min, were tested on hardness.

Vickers hardness was determined on an HMV-2000 Shimadzu. The expected indentation was smaller than 0,05 mm, which was small enough for the interspacing between the test positions of 0,2 mm, as was advised in EN 1043-2:1996. The load on the diamond was 200 g. and the duration of the impression was 5 seconds.

3.4.4 Bending testing

For the longitudinal bending tests new layers were friction surfaced. These experiments were performed with the same parameter settings as were selected for the specimens for the hardness specimens. The bend tests were performed on a Zwick tensile test machine. The schematic set-up of the specimens and the equipment is shown in Fig.28, a photograph of the set-up is depicted in Fig.29. This is similar to the procedure described by Thomas (1985) [10] and by Nicholas and Thomas (1986) [3]. This procedure is similar to the bend test procedures as described in EN 910:1996.

Fig.28: Unrestrained longitudinal bending test [3].

Fig.29: Set-up bending tests.

The test set-up in the test machine was first tested with a dummy plate with about the same dimensions as the specimens. Since the equipment failed with a vertical force of 104 kN, the testing with the 13mm thick plate was considered to be impossible. The plates then were milled down to 6mm. The width of the plate was kept 50mm. The force now used for the bending tests was reduced from circa 104kN (13mm thickness) to circa 27kN. The piston had a diameter of 30mm.

3.4.5 SEM

The specimens showed no dilution under the light microscope. To get a better indication of the dilution of stainless steel in mild steel, a scanning electron microscope was used for detecting element concentrations in the interface area.

The interval between two measurements was 0.5μ m. This way a good impression of the dilution was obtained. On each specimen 57 measurements were carried out in a line perpendicular on the interlayer. The measurements start in the bulk material of the coating and end in the bulk of the substrate. The SEM used for the measurements was a Zeiss DSM 962.

3.5 Multilayer friction surfacing

Fig. 30 shows how a second layer is surfaced next to the preceding one. This preliminary investigation was only performed with one set of parameters. The deposits were not machined before placing the next coating against it, even though this was suggested by Shinoda [7]. In the same article he states that with increasing overlap the bonding defects also increase. Therefore the second and third layers were placed against the former ones with a minimum overlap of circa 1mm [7]. Because the edges were not machined before surfacing the new layer against the former one, the rotational direction was chosen in such a way that the front side of the rod was pushing against the side of the former layer. In this way it was expected that the plastified material would be forced underneath the cold laps of the former coating layer. The new deposit was made at the retreated side of the former layer as was suggested by Nicholas and Thomas [3].

The result of the multilayer surfacing was examined visually and optically as has been described for single layer surfacing.

Fig.30: Multilayer surfacing.

4 RESULTS AND DISCUSSION

4.1 Equipmental performance

The equipment used for the experiments was never used for friction surfacing before. The robot was used only for friction stir welding. However, the basic principles for friction stir welding and friction surfacing are similar. For both processes the main parameters are axial pressure, rotational speed of the rod and traverse speed along the substrate. Therefore no adjustments had to be made on the robot. The choice for the TRICEPT 600 was based on of the possibility to move the robot along a path with force control in the axial direction. The force feedback system includes recording this force data during a weld. The correct force is implemented in the matrices.

All parameters and measurements during and after the welding are given in Appendix A.

When the force was higher than 1900 N, the stud frequently blocked. The blocking probably occurred because the frictional force became too high for the spindle to keep on rotating the rod when the pressure was increased. Therefore the stud did not get the chance to plastify. Applying an initiation force of maximal 1900 N during the initiation time solved this problem.

Since with the first attempts the surfacing layers showed a lack of material at one side of the coating, the rod position was tilted under a slight angle of 0,5 °.

4.2 Visual examination

After the deposits were produced, they were visually examined, the thickness and width were measured and pictures were taken from the topside. The measurements and pictures are placed in matrices in Appendix B. The results of the visual inspections were compared with the measurements on the macrographs. The welds show, as can be seen in the pictures, that a minimum velocity is needed in order to get a continuous surfacing line. If the rod is moved too slowly over the substrate, the surfacing 'layer' piled up at a local area. At a certain stage the stud slid of the big dot and started making a new dot. The higher the velocity the better the surfacing looked as shown in Fig.31.

Fig.31: Influence of low traverse speed on the weld appearance, top view.

When the velocity of the rod along the substrate was too high then not enough material was deposited and the surfacing layer became irregular as is shown in Fig.32.

Fig.32: Influence of high traverse speed on the weld appearance, top view.

With increasing traverse speed thinner deposition layers were produced. This was established by measuring the thickness of the deposit at several places along the advanced side. When applying higher force, the deposited material was wider smeared on the surface and the weld was more regular (Fig.33).

4.3 Optical examination

After the substrates were polished and etched, the specimens were examined under the microscope and macrograph and micrograph pictures were taken. The macrographs were put in a matrix for evaluation (Appendix C).

If the traverse speed of the rod over the substrate was increased, the macrograph pictures show that the deposited layer decreased in thickness (Fig.34). Also the width of the deposit decreased slightly.

The decrease in thickness and width can be explained by the fact that because of the higher traverse speed of the rod the deposited material has to be devided over a larger area.

The heat affected zone became smaller with increasing velocity because the time of heat input per area is shorter with higher traverse speed.

In Fig.35 is clearly to see that with increasing force the layer thickness decreased and the deposit width increased. Also the HAZ increased with increasing force implying a higher heat input.

The findings and related tendencies on friction surfacing with fixed equipment as mentioned in the literature are listed in Table 5. As can be seen, there is agreement between the literature and the results with the robot.

Table 5: The effect of the parameters on the properties of the surfacing layer and efficiency.

| | Incre | asing force | Increasing |
|-----------------------|--------------|-------------|----------------|
| | | | traverse speed |
| Width | ↑, | ↑ [7, 17] | \downarrow |
| Thickness | ↓, | ↓[7] | ↓, ↓ [17] |
| HAZ | \uparrow | | \downarrow |
| Rod efficiency | \downarrow | | \uparrow |
| Deposition efficiency | -, | ↓[9] | - |

The quality of the bonding between the deposit and the substrate was studied with a higher magnification. The emphasis was put on the interface. The following pictures give an impression of cold laps, good bonding and bonding with voids.

Fig.36 shows the lack of bonding between the cold lap of the white surfacing layer and the substrate. In this picture also the structure is shown, including part of the HAZ at the right side.

Fig.36: Picture of the microstructure at the side edge, showing clearly the lack of bonding at the cold laps.
Fig.37 depicts voids at the right side of the interface, while the left side shows good bonding. The white austenitic deposit and the etched ferritic substrate show no interlayer in between them. Also no mixture of the two metals is observed.



Fig.37: Microstructure with HAZ, voids and perfect bonding areas.

As described before, three areas can be distinguished. An area with good bonding qualities is an area where no voids were seen at the interlayer. A second area is one with good bonding though interfered with voids at the interlayer as is seen in Fig. 37. The last area is found at the sides of the deposit and has no bonding at all. This area includes the cold laps of the deposit. These three areas were measured and a percentage of good bonding with no voids was calculated as well as the percentage of the cold laps. The results are given in Appendix C. Also the absolute width of perfect bonding area is given here.

Because only one cross-section per deposit was taken and because of the accuracy of measuring, only a global impression can be formulated. There is a trend that a higher axial pressure results in a higher percentage with good bonding.

4.4 Efficiency of the rod

Depending on the purpose of the deposit, the optimal parameters for friction surfacing might be different. The rod efficiency can help to decide on the amount of rod material needed. At first measurements of the length and thickness of the flash-up were made. The thickness did not vary significantly with the parameters. The length of the flash-up tended to increase with increasing axial pressure and it tended to decrease with increasing traverse speed. This is expected in regard to the calculations on the rod efficiency. In Appendix A, the weight and length of the rods are presented. In Appendix D the results of the efficiency are given in a matrix with the surfacing parameters. As expected the efficiency of the rods tended to increase with pressure and tended to decrease with the traverse speed.

The reason for the efficiency must be found in distribution of the heat input over the rod and the substrate as was suggested by Shinoda et al. (1998) [7] and by Li et al. (2000) [9]. They state that the rate of heat input, going to the rod, increases with higher rotational speed. Similar, the rate of heat input going the rod will increase with increasing pressure. The shifting of the rate of heat input to the rod causes a greater

consumable feed that is transferred mainly to the flash-up. Increasing the traverse speed results in a reduced consumable feed, which also confirms the results of the visual examination. Therefore, the decrease of consumable feed results in an increase of rod efficiency.

4.5 Hardness testing

The maximum hardness of the substrate and the deposit, was expected at the interface. This was found by Shinoda et al. (1998)[7] and is confirmed by the graphs made of the hardness testing results of this study.

Because the surfacing layers did not have the same thickness and the first indentation of the hardness tests was always made at 0,2 mm from the top of the surface layer the indentations around the interlayer were not at the same place. To be able to see any relations in the hardness tests the interface layer was taken as reference (Appendix E). Therefore the graphs all were translated so that the interface was normalised with the interlayer as origin.

The results of the hardness tests of the deposits were examined with constant axial force and varying traverse speed (Fig.38).



Fig.38: Hardness distribution of specimens obtained at different traverse speed.

This clearly shows that the maximum hardness for both materials is at the interface. In the review a relation was given between hardness and rotational speed. Here no relation between hardness and traverse could be found.

The results of the hardness tests were also examined with constant traverse and varying axial force by interpreting the graphs (Fig.39).



Fig.39: Hardness distribution of specimens at different axial force.

No relation could be found between hardness and axial force. The problem of finding a relationship between the parameters may be because of the fact that the used parameters only resulted in minor variation.

4.6 Bending testing

The bending test specimens were all except one able to bend over 165° without the coating layer separating from the substrate. When examining the welds after the bending, some of the coating layers had cracks in the sides as is shown in Fig 40. The cracks in the retreated side were always higher in number and more severe than in the advanced side. The results show that it is very likely that the crack initiation starts at the retreated side. This is understandable since the advanced side on the coating layer is very regular while the retreated side is irregular.



Fig. 40 Bend specimen with a severe crack at retreated side and a small crack at the advanced side.

The results of the bending tests are given in more detail in Appendix F. The specimens which were surfaced with an axial force of 3,6 kN or lower had all cracks at the retreated side and at the advanced side. When 4,8 kN was applied most of the bend specimens had a single small crack at the retreated side. In only one of the four specimens, which were produced with 6 kN axial force, a small crack at the retreated side was observed. All specimens that were surfaced with an axial force of 7,2 kN showed no cracks at all. This indicates that higher axial force during friction surfacing results in better bonding. This can be explained by a better contact between the deposit and the substrate during the surfacing, which ensures a closer contact between the lattices of the different metals during the friction surfacing. Because the width of the HAZ increases with increasing pressure (Fig. 35), a higher heat input is expected. This may cause a higher dilution because of diffusion along the interface.

4.7 SEM

In stainless steel chromium and nickel are present in high concentration and the intake of these elements in the mild steel substrate could easily be determined with scanning electron microscopy. The dilution of mild steel in stainless steel was very difficult to establish because of the low concentration of the alloying elements. A graph of the results is given in Appendix G.

The expected dilution layer, according to the literature, is less than 20μ m [6, 11]. By examining the specimens with SEM a dilution was found of approximately 5μ m for the element chromium. The experimental value is within the range mentioned in the literature. The differences can be explained by differences in rod diameter and traverse speed of the rod over the substrate. The diffusion of chromium in the substrate also can be calculated with the following equation:

$$D = D_0 \exp(-Q/RT)$$

(1)

where D is diffusion coefficient, D_0 is the diffusion constant, Q is the activation energy, R is the gas constant and T is the temperature in Kelvin [23, 24].

The maximum coating temperature can reach high levels of typically 90% of the melting point of the substrate [25].

With the diffusion coefficient the radial diffusion distance r from the origin after a period of t seconds can be calculated with the equation [23]:

$$r = 2,45(Dt)^{1/2}$$
 (2)

With the diameter of the rod and the traverse speed over the plate the period where the temperature is maximal was calculated. For this period the diffusion was calculated, resulting in a penetration depth of chromium in the substrate of circa 2μ m. The calculations are shown in Appendix G.

According to the SEM examination the dilution is higher. This can be explained by the fact that the coating layer was cooled down slowly. At first because while the rod moved over the deposit it slowed down the cooling process by continuing transferring heat in the work piece. Secondly when the heat input of the process had no influence anymore on the cooling process the coating cools down in the open air and was not quenched. This all can result in a deeper penetration of elements in the substrate. Furthermore the diffusion coefficient of chromium in stainless steel was used in the calculation. The diffusion coefficient of chromium in ferritic steel is higher than the self-diffusion coefficient of chromium in ferritic steel is higher than the self-diffusion coefficient of chromium in the mild steel.

4.8 Multilayer Friction Surfacing

Since only one experiment with multilayer friction surfacing was done, no comparison with other results can be made. The result is very promising and should be further examined. The experiment was examined on visual appearance and under a microscope. Fig. 41 shows a specimen with three layer deposits.



Fig. 41: Multilayer friction surfacing deposit.

The multilayer surfacing is carried out with the traverse of the different layers in the same direction. Another option is to have the layers next to each other friction surfaced in opposite directions.

Fig. 42 shows the macrostructure of a multilayer friction surfacing. It shows that the material is not forced under the cold laps of the former layer and an overlap on the former layer is formed.



Fig. 42: Macrostructure of multilayer coating

With the parameter chosen for this experiment better results will be expected if the cold lap will be taken off the former layer prior to the next layer.

The rotational direction also should be taken into consideration to improve the bond quality between the single deposits.

4.9 Resume of the results

In Fig.43, three areas are observed. In the red area the experiments showed that the quality of the coating or the bonding was unsatisfactory. This was caused by a lake of pressure or a too low or a too high traverse speed of the rod over the substrate. The grey area is the area where still experimental work has to be done. In the green area the results of the experiments were satisfactory and further research should be carried out with these parameters.



Fig.43: Schedule of the results of the experiments.

This schedule is only for a fixed rotational speed of 3000 rpm. If the rotational speed is increased, the expectation for the schedule is that the green area will move downwards. This will be because the higher heat input caused by the higher rotational speed may cause a need of less force for a good bonding quality. Furthermore, the green area in the schedule might extend to the right side, because of the higher heat input the consumable feed will most likely increase. Therefore the traverse speed can be higher.

When the process is carried out under water, the heat losses will be higher and therefore a higher heat input is required for the same quality of the deposits. This means that or the rotational speed should be increased, the force should be higher or the traverse speed should be lower

5 DISCUSSION

In this chapter the results obtained in the experimental work will be discussed in comparison with some models from literature on heat generation, temperature distribution and mass flow during friction welding. For friction surfacing no models are present. However, the initiation period during friction surfacing is relatively the same as in friction welding. Therefore, models of temperature distribution for friction welding can be used as a starting point to explain the phenomena occurring.

Microstructure depends on the thermal history of the specimen, in particular the peak temperature and cooling rate. Although the temperature distribution is not measured, the results of the microstructural examination and the hardness measurements could give some additional information on the heat transport process.

The distribution of stresses is related to the temperature fields in the specimens and the thermal expansion coefficient of the materials used. Some remarks on the internal stresses occurring during friction surfacing will be made.

Some remarks are made about the problems rising when a description of the mass flow behaviour during processing is attempted.

Compared to friction welding the surfacing process is more complex. The complexity increases, due to the added traverse speed, which influences the heat input, the cooling rate, the action time and the deposition of the material.

Finally some points of attention and ideas for modelling friction surfacing, regarding the relationship between the parameters, quality state variables and the coating quality, are given.

5.1 Heat generation and heat transport.

Under compressive force between a stationary workpiece and a rotating object (rod) frictional heat is produced in a concentrated area. This heat plastifies the material and results in bonding between the two materials. In the process no melting occurs. As a first estimate, a model of Grong [26] can be used to predict the temperature of the friction area. He stated that during the process a constant rate of heat (q_0) is liberated per period of time. In a small area, the amount of heat (dQ) produced in the process during a period of time (dt') is given by the following equation:

$$dQ = q_0 dt'$$
(3)

At time t the heat will cause a small rise of temperature (dT) in the material, according to equation (4):

$$dT = (q_0 dt'/A) / (\rho c (4\pi a (t-t'))^{1/2} \exp(-x^2/4a (t-t')))$$
(4)

where A is the cross sectional surface area of the rod, ρc is volume heat capacity , a is thermal diffusivity and x is the distance from the heat source.

After integration over the processing time and some manipulations the temperature of the contact section at the end of the heating period can be written as:

$$T-T_0 = (T_h - T_0)(t/t_h')^{1/2} \{ \exp(-x^2/4at) - ((\pi x)^{1/2}/(4at)^{1/2}) \operatorname{erfc}(x/(4at)^{1/2}) \}$$
(5)

where t_h denotes the duration of the heating period, T is the temperature at time t, T₀ is the ambient temperature, T_h is the temperature at the end of the heating period and $(T_h - T_0)(t/t_h)^{1/2} = q_0(t)^{1/2}/A\rho c(\pi a)^{1/2}$.

In this model the division of the temperature in the rods is considered uniform over the full friction surface.

In Fig.44 the trend of this equation is schematically depicted. In the friction welding process after the welding period the rotation is stopped and the cooling period starts. In friction surfacing due to the travelling heat source condition the cooling of the deposit and the substrate is much more gradually and associated with the action time.



Fig.44 Profile of temperature as function of time [26].

Mitelea and Radu [27] used numerical analyses for heat input and thermal field calculations. For modelling the following simplifying hypotheses were made:

- 1) The materials have homogeneity and isotropy of all their properties.
- 2) The entire heat generated during friction welding is produced only on the frontal surfaces and only during the period of time when the frontal surfaces are in contact and rotational movement takes place at the same time.
- 3) Friction between two similar materials is considered. This assumption is made to be able to estimate a more reliable friction coefficient.
- 4) The heat is not produced uniformly. The centre of the rotating workpiece has a rotational speed of zero and at the edge of the rod the highest velocity is reached, implying that the highest heat input is generated at the edge of the rods.

One of the major problems of modelling the heat flow with finite element method is to determine the quantity of heat generation during the friction process.

To solve this problem, the friction contact area is divided into a large number of elementary circular surfaces determined by radius r and r + dr, with an area of da = 2π .r dr (Fig.45).



Fig.45: Elementary surface element

The quantity of heat generated on this elementary surface is:

$$dq = \omega.M_{fr}.da$$
(6)

where ω (= 2 π n) is the angular speed (n is revolution speed) of the components which are friction welded and M_{fr} is the friction momentum. The friction momentum can be expressed as a function of friction coefficient (μ) and axial pressure (P) as follows:

$$M_{fr} = r.F_{fr} = r.\mu.P$$
⁽⁷⁾

If equation (7) is inserted in equation (6) the elementary quantity of the heat generated on an elementary surface da is given by the next equation:

$$dq = 4 \pi^2 . r^2. \mu . P. n dr$$
 (8)

Integrating this over the radius gives the total heat (Q) generated on the entire surface

$$Q = 4/3 \pi^2 . \mu . P.n.R^3$$
(9)

where R is the radius of the total surface.

The only element, which raises problems, is the friction coefficient, as it is dependent on temperature and material combination. However, it is stated that as the von Mises flow criteria is to be respected, the friction coefficient is limited to the value of the ration between normal effort and tangential effort and can be taken as 0.577. Although the heat generation is considered to be uniform in time, the production of heat is not uniformly distributed over the surface. Mitelea and Radu [27] modelled three different cases for heat distribution as are shown in Fig.46.



Fig.46: Models of heat distribution on the friction surface

In Fig.46A, the outside of the rotating rod the heat generation is highest and in the centre of the rod it is minimal because the angular speed is zero. In Fig.46C an evenly distributed temperature profile is shown. This could be realised with a high heat conductivity and a small diameter of the used materials. The realistic model is given in Fig.46B, where the heat generation is concentrated on the circular sector in between radius R/3 and 2R/3. In this situation also cooling of the edge is taken into consideration.

During friction surfacing a traverse speed is added which causes an even higher cooling rate since the rod is constantly moved to a relatively cold area on the substrate.

5.2 Calculations on heat input in experiments with robot

The calculated heat input by means of the model of [27] is compared with calculations of the required heat for the creation of the HAZ, the deposited layer and the plastification of the rod material.



Fig.47: Deposit of friction surfacing at the initiation.

The initiation period of the friction surfacing experiments is comparable to the stationary situation used in the above models. In Fig.47 the initiation area of one of the friction surfacing experiments is shown. The initiation time was 4 seconds and the diameter of the rod was 10mm. The force in the calculations is varied and the HAZ is measured in the macrographs of the different experiment where the traverse is kept constant. In these calculations the temperature taken is the average of the estimated maximum temperature and the estimated temperature at the border of the HAZ.

In Table 6 the calculated heat input is given for the different experimental conditions but should be handled with care, since it is a rough estimation.

In the table the following heat quantities are listed:

- The axial force of the specific experiment.
- Q_{model}: The heat input calculated by equation (9). The input parameters are the axial force (variable), the radius of the rod (10 mm) and the rotational speed (3000 rpm).
- Q_{SS}: The heat required to elevate the temperature of the substrate to 1000°C. The amount of material is estimated as a circular bar. The width of the substrate and the reinforcement height are used in the calculation. The heat capacity of stainless steel is 450 J/kgK, and the density is 8,0*10³kg/m³.
- Q_{HAZ}: The heat required to create the heat affected zone. The volume of the HAZ area is estimated by a spherical section. The measured depth of penetration and the top width of the cross section are used in the calculations. The heat capacity of mild steel is 470 J/kgK, and the density is 7.8*10³kg/m³

- Q_{rod}: The heat required to elevate the temperature of the rod to 1000°C over a length of 15 mm.
- Heat loss: the difference between Q_{model} and the summation of Q_{SS}, Q_{HAZ} and Q_{rod}. The heat loss consists of radiational heat losses to the environment, heat conductivity into the base metal and to the robot, and heat loss to the flash up.

As is clearly shown, according to Mitelea and Radu [27] a more heat is produced than absorbed in the HAZ, the deposit and the rod. This is to explain by the heat flow not stopping at the edge of the HAZ. Furthermore the substrate is a plate and not a rod what results in a higher heat flow. The heat also flows away through the rod into the robot. Also the temperatures are estimated. The radiation to the environment is not taken into consideration. The values found for the heat input given by Mitelea and Radu [27] are within acceptable range to take them as an estimation for the initiation period and the model is a good start for further modelling on heat input during the friction surfacing process.

| F (kN) | Q _{model} (J) | Q _{SS} (J) | Q _{HAZ} (J) | Q _{Rod} (J) | Heat losses (J) |
|--------|------------------------|---------------------|----------------------|----------------------|-----------------|
| 2,4 | 5801 | 121 | 17 | 4252 | 1411 |
| 3,6 | 8701 | 144 | 68 | 4252 | 4238 |
| 4,8 | 11601 | 166 | 106 | 4252 | 7077 |
| 6 | 14502 | 149 | 131 | 4252 | 9970 |
| 7,2 | 17402 | 153 | 170 | 4252 | 12827 |

Table 6: The heat input in different parts of the system according to calculations.

From the values in Table 6 a tendency can be observed that when the axial pressure is increased the size of the HAZ increases, what is an indication of an increased heat input. A remark should be made that many assumptions are made in the calculations. For example, in the above table 6 the heat input in the rod is kept constant although in paragraph 2.2.1 and Fig.3 is shown that the heat distribution in the plate and the rod is not constant.

According the model of Mitelea and Radu [27], increasing the pressure results in an increase of the heat input. In the experiments with friction surfacing the higher heat input is evident to the increase in the size of the HAZ. The increase of the heat input with the increase of the axial force is clearly shown in Fig.48.



Fig.48: Penetration depth of the heat affected zone as a function of the axial force. Rotational speed is 3000 rpm and traverse speed is 450 mm/min.

The higher heat input will also result in a larger plastified zone and therefore a higher consumption rate of rod material. With increasing pressure, the larger plastified zone will result as shown in chapter 4 in a large flash up and therefore a lower efficiency (Fig.49).



Fig.49: a) Usage of the rod per surfacing length (app. 50 mm) and b) rod efficiency as a function of the axial pressure.

Rotational speed is 3000 rpm and traverse speed is 450 mm/min.

Regarding an increase of the rotational speed, Mitelea and Radu [27] state that the heat input will increase as well. Trends observed with increasing pressure can be expected with increasing rotational speed.

The traverse speed of friction surfacing is not included in the models of heat generation of Grong [26] and Mitelea and Radu [27]. However, by traversing the hot rod is continuously moving over a relatively cold substrate. If this is taken into consideration, it is to be expected that the heat input will decrease with increasing traverse speed. This results in a smaller plastified area of the rod, a smaller heat affected zone and a reduced consumption of the rod. The heat conduction especially into the base metal will increase. The heating per unit weight will be much lower. Fig.50 and Fig.51 show the influence of traverse speed on the experimental results of the above properties. The material of the rod is more efficiently deposited and the amount of material in the flash up is reduced.









Fig.51: a) Consumption of the rod and b) rod efficiency as a function of the traverse speed.

Rotational speed is 3000 rpm and axial pressure is 4,8 kN.

In the case of friction surfacing the geometrical situation is different because one of the rods is replaced by a plate.

5.4 Microstructural development and hardness measurements

Microstructure pictures are taken of the HAZ. This way an impression of the temperatures at different places is obtained. At the interface the structure of the mild steel has a coarse grain structure as is shown in Fig.52. Because of this structure, the temperature must have been approximately 1200^oC during the friction surfacing process.



Fig.52: Coarse grain structure in the substrate at the interface area.

From about 0,5 mm to 0,85 mm from the interface an area with fine grain structure is registered that has ferrite growth on the former austenite grain boundaries which indicates a temperature of circa 900^oC (Fig.53).



Fig.53: Fine grain structure in the HAZ of the substrate

In Fig.54 the base material is shown. The generated heat of the friction surfacing process has not affected the structure with the carbon layers



Fig.54: Base material of the substrate.

In Fig.55 is given the temperature profile during friction welding as a function from the distance from the friction contact area according the model of Mitelea and Radu [27]. In this picture is clearly to see that the temperature in the materials can reach over 1200^oC and then rapidly decreases. This was also observed by examining the microstructures in the HAZ.



Fig.55: Temperature division during friction welding as a function from the distance from the friction contact area [27].

During the friction surfacing process the rod material is plastified and deposited on the substrate. The substrate experiences a heat influence during the process. After cooling down the specimen residual stresses are present in the sample. This was very well observed when the plates with the specimens for the bending tests where milled down to 6 mm. Then the plates were curved, showing that the deposit wanted to shrink more then the substrate allowed it to do. In future testing applying strain gauges can give an impression on the residual stresses. The process then also has to be standardised on the thickness of the substrate in order to be able to compare the residual stresses in the different experiments.

5.6 Metal transport

Mass flow during friction surfacing is very complex because of the many different aspects occurring during the process. The pressure pushes the material to the sides. During the process the rod ends up generating heat on the deposit surface and not on the substrate. This is one of the possible reasons why the dilution of the materials is so little. Also the rod moves forwards what results in a deposit lag as is shown in Fig.7. The deposit lag and the rotation on the deposit give an uncertainty in where the material is deposited and in the way the material may be stirred. To obtain more information on this subject experiments should be carried out, with for example tracers with different diameters in the rod.

The diffusion of the elements from the deposit to the substrate and visa versa is most likely related to the heat input since a higher heat input implies a higher temperature or a longer period with high temperature. In equation (1) is given that with increasing T the diffusion coefficient D will increase and in equation (2) the relation between r and t is shown. To establish this assumption, more specimens should be examined under the SEM.

5.7 Relationship between the parameters, quality state variables and the coating quality.

As has been shown in the paper, research so far has revealed that in friction surfacing the axial force, the rotational speed and the traverse speed are of critical importance for the final quality of the coating and the bonding.

Vitanov et al. [28] have tried to optimise the procedure for friction surfacing. Therefore they involved in the study:

- 1. an appropriate set-up for in-process precision measurement of the temperature (T), torque (M), bonding time (t_{tb}) , spindle rotational speed and force.
- 2. An estimation of correlation between process parameters: traverse speed (V), axial force (F), rotational speed (N) and the coating state variables: thickness (C_t) , width (C_w) and bonding strength (C_{bs}) .
- 3. Development of a decision support system to utilise temperature, torque and bonding time.

In Fig.56 a diagram is given of the adopted experimental approach and indicates dependencies between process parameters V, N, F and the coating state C_t , C_w and C_{bs} , as well as the indicators M, F and T.



Fig.56: Schematic representation of experimentally relationships, between controllable, observable and quality parameters in the friction surfacing parameters [28].

The results of the experiments done with the robot at GKSS show also the relation between F, V and thickness and width of the coatings. Regarding the HAZ, the temperature T is related to the traverse speed V, which is not shown in Fig.56.

Vitanov et al. [28] states that an increasing thickness decreases the bonding strength. They also state that an increase in pressure decreases the thickness and increases the bonding strength.

The question that now raises, is: is the bonding strength increased because of the increase of the pressure or because of the decrease in thickness? In the statement: 'an increased traverse speed decreases the thickness and the bonding time, therefore the bonding strength decreases' Vitanov et al. [28] here contradict themselves.

In chapter 4.9 a process window is presented. In the green area successful surfacing can be performed. In regarding to the discussion above the tendencies in this window can be explained as follows

For low axial pressure the bonding is not established because the contact between the rod and the substrate is not sufficient and not enough heat is produced.

When traverse speed is increased the minimum amount of axial force increases in order to create a good bond, since the heat input per unit time should be higher. Although no experiments were conducted on the influence of the rotational speed on the friction surfacing process it is to be expected that the trend is similar to the trend observed for the axial force.

6 CONCLUSIONS

The results achieved within the described work are very promising. The following conclusions can be drawn in summary:

- The parameter sets for friction surfacing of stainless steel on a mild steel substrate performed with rigid machinery vary to such an extent that a comparison with the parameter found for robotic friction surfacing as described in this thesis, is very difficult.
- The experiments on friction surfacing were done with a TRICEPT 600 robot. Since this technique has never been applied before with a robot, new parameters for friction surfacing had to be found. Regarding the bond qualities and the appearance of the welds a minimum force of 3,6 kN is required. The maximum axial force used for the experiments was 7,2 kN. It was the maximum force that could be used during the experiments, higher forces might improve the process.
- For the traverse speed a minimum as well as a maximum speed was found. The minimum traverse speed was found to be 330 mm/min. When the speed was lower, the lack of bonding was unacceptably high. The maximum traverse was about 570 mm/min. With higher speeds the appearance of the weld showed lack of material being deposited. Due to the lack of material, the retreated side of the deposit became too irregular. The irregularity of the edge implies that the width of the deposit can not be predicted. Also for eventual use of multilayer friction surfacing the irreg\ularity may be unacceptable.
- The width, thickness and HAZ decrease with increasing traverse speed due to the lower consumable feed rate. The width and the HAZ increase and the thickness decreases with increasing axial force.
- The quality of bonding was determined in two ways. Firstly, based on metallographic analysis of the macrographs and micrographs. A bonding percentage was established. Even though a systematic error was present in the measurements, still a clear trend can be seen increasing bonding quality with higher pressure.
- The second way of determining bonding quality involves bending tests. These resulted in general in a complete bend of over 165°. Additional qualification was made on initiation cracks in the cold laps of the deposits. Based on these all tests with an axial force over 6 kN succeeded without visual damage. This clearly demonstrates that the quality of the deposit is good to very good. The one question that still remains, whether the deposit lost integrity in the bend area already and kept in place only by the bonding in the unbend parts of the specimen.
- The rod efficiency increases with the velocity and decreases with the axial force.

7 RECOMMENDATIONS

- In future research the microstructure and flowlines of the deposit should be examined.
- A model for the thermal phenomena during friction surfacing is still not available and should be made.
- The work that has been done is limited because only 10mm diameter rods have been used. Examination with different rod sizes should be carried out.
- Only the axial force and the traverse speed have been varied. No remarks can be made on the influence of the rotational speed.
- The used robot had a limited stiffness. Therefore all experiments were performed with side guide plate. With a stiffer robot friction surfacing should be possible without the guide plate. This will also give the possibility to do underwater friction surfacing and three-dimensional friction surfacing.
- Another technical aspect is that a guide system for the stud would make it possible to use longer studs.
- Also a thought should be given to a system, which takes away the flash-up during surfacing so that the appearance of a double flash-up can be prevented and still the full rod can be used.
- Multilayer surfacing is done in only one way. The result look promising and further investigation should be done in rotational direction of the rod in relation to the former layer. Furthermore it should be taken into consideration if the layers should be made an up and down direction or that every new layer should start at the same side.
- A suggestion to examine this is by cutting the deposit on the top of the bend specimen. Before doing this, first one should think carefully about the test qualifications.
- Two other bend directions should be considered as well. During this work the bend tests have been performed perpendicular on the deposit. A test where the specimen is on the side and a parallel bend test have not been performed. These tests might give more information on the bonding quality.

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APPENDICES





Friction surfacing with a robot

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Contents

- Introduction to friction welding
- Friction surfacing
- Experiments and results
- Conclusions
- Questions





Friction welding techniques



Friction pipe welding

- welding pipes together
- rotation of pipe
- flash up





Friction welding techniques



Friction stir welding

- non-consumable rod
- welding plates together





Friction surfacing process



- Deducted from friction welding
- Consumable
- Coating layer





Applications for Friction surfacing

- Corrosion protection
- Wear resistance
- Repairs of worn out parts





Friction surfacing process



- Side view
- Deposition at the front





Friction surfacing equipment







Friction surfacing set-up







Friction surfacing







Friction surfacing









Friction surfacing (front view)






Friction surfacing

Film





Friction surfacing









Development flash-up







Influence on deposit

- Rotational speed
- Axial pressure
- Traverse speed
- Used materials





Friction surfacing process



- Rotation and traverse
- Action time





Friction surfacing process



• Offset of the centre line





Examination of the deposits

- Macrostructure
- Microstructure
- SEM
- Hardness tests
- Bending tests













Influence of axial force

Width and thickness of deposit







Influence of Traverse speed















Bonding quality



ষ Cold laps

a Voids





Interface













Hardness

Hardness (axial force = 3,6 kN)



- FS061; v = 330 mm/min
- FS062; v = 450 mm/min
- FS063; v = 570 mm/min
- FS084; v = 630 mm/min





Set-up bend test







Bend tests







Bend tests







Bend tests

















- Rotation direction
- Edge side
- Traverse direction







Edge filling:

- Clockwise
- Counterclockwise

a clockwise; b counterclockwise





















Conclusions

- Minimal axial force 3,6kN
- Traverse speed related to axial force
- Failure starts at retreating side
- Small HAZ
- Little porosity
- Negligible dilution
- Good bonding





Questions?





Questions ?