1.1 W5: Material, welding- and conditioning technology at the deep drilling

1.1.1 Project Overview

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<th>Project Nr.</th>
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<th>Project leader, institution, location</th>
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<td>W5</td>
<td>Material, welding- and conditioning technology at the deep drilling</td>
<td>Material-, joining-, automation- and conditioning technology</td>
<td>Prof. Dr.-Ing. habil. Dr.-Ing. E. h. Dr. h. c. Fr.-W. Bach, Prof. Dr.-Ing. H. J. Maier LUH (IW) Prof. Dr.-Ing. B. Denkena, LUH (IFW)</td>
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Participating institutes and institutions of the universities and external institutions:
- Institute of Materials Science (IW), Leibniz Universität Hannover
- Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität Hannover

List of participating scientists and engineers:

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<tr>
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<th>Subject area</th>
<th>University institute or non-university institution</th>
<th>Position is financed by gebo funds (indicate by X)</th>
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<tbody>
<tr>
<td>Prof. Dr.-Ing. habil. Dr.-Ing. E.h. Dr. h.c. Fr.-W. Bach</td>
<td>Material science</td>
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<td>Prof. Dr.-Ing. H. J. Maier</td>
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<td>Dr.-Ing. Th. Hassel</td>
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<td>Dipl.-Ing. A. Varahram</td>
<td>Material science / welding technology</td>
<td>IW</td>
<td>X</td>
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<tr>
<td>Prof. Dr.-Ing. B. Denkena</td>
<td>Production engineering and machine tools</td>
<td>IFW</td>
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<tr>
<td>Dipl.-Ing. Leif Behrens, Dipl.-Ing. Stephan Woiwode</td>
<td>Production engineering and machine tools</td>
<td>IFW</td>
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1.1.2 Research Program

1.1.2.1 Summary

Aim of the project is the simplification of the tubular handling at the well, where at the common applied tool joints for the elongation shall be replaced with the electric arc welding. With this method especially the application of endless coiled tubes shall be realized. Main research points are the implementation of the weld seam preparation, the development of the welding techniques as well as the removal machining of the joint patch and the cutting of the drill pipe at the deconstruction.
1.1.2.2 Relationship of the project to the overall research context and networking with other projects

One goal of the whole joint research project is to reduce the drilling costs under “hot-hard-rock” conditions. In the project W5 technologies, which simplify the tube handling, shall be investigated. These technologies were applied to replace the threaded connections for the elongation by electric arc welding. The relationship of the project to the overall research context and networking with other project results of the necessary input (requirements of the drill techniques and automation, geohydraulic parameters, characteristics of the well and drill pipe load profile) as well as its output (feasibility of the coiled-tubing by welding connections, characteristics of the drillstring and processdata within the component assembly).

1.1.2.3 Work packages executed relative to plan and results achieved

WP1: IW: Conception

Target of gebo sub-project W5 is the substitutionof threaded connections by fast connecting with less production time for drillpipes. MIAB welding distinguishes itself by short cycle times and easy automation which lead to an expected reduction of drilling costs and drilling times respectively [4, 5].

Task of working package 1 is the determination of welding parameter fields to configure further construction assemblies of a MIAB test system. After a detailed literature research on MIAB welding processes welding parameters like required arc deflecting force and coil design could be calculated. These values are used for further configurations of the test rig.

Calculation of the force acting on the magnetic arc

In the first instance the required force to deflect the magnetic arc on the atmosphere is calculated. It is assumed that the arc can be treated as a cylindrical current-carrying conductor. The magnetic field strength \( H_L \) is defined as [1]:

\[
H_L = \frac{F_L}{I_L}; \quad [H_L] = \frac{A}{m}
\]

(1)

Entering the magnetomotive force \( F_L = I_L n_L \) and the circumference of the conductor respectively the arc \( l = 2\pi r \) into equation 1, \( H_L \) is:

\[
H_L = \frac{I_L n_L}{2\pi r}
\]

(2)

The arc radius \( r \) is assumed to be 0.75 mm. The current \( I_L = 500 \text{ A} \) and the number of turns of the arc \( n_L = 1 \). The magnetic field strength \( H_L \) is:

\[
H_L = \frac{500 \text{ A} \cdot 1}{2\pi \cdot 0.0075 \text{ m}} = 10610.33 \frac{A}{m}
\]

(3)
With the magnetic field strength $H_L$ the magnetic flux density $B_L$ can be determined to:

$$B_L = \mu H_L; \ [B_L] = \frac{Vs}{m} = T$$  \hspace{1cm} (4)

With $\mu = \mu_0 * \mu_r$, $\mu_r = 1$, $\mu_0 = 4\pi * 10^{-7} \frac{Vs}{Am}$ it is:

$$B_L = 4\pi * 10^{-7} \frac{Vs}{Am} * 10610.33 \frac{A}{m} = 0.0133 \frac{Vs}{m^2} = 0.0133 T$$ \hspace{1cm} (5)

With the help of the magnetic flux density $B_L$ from equation (5) the required force for the arc deflection $F_L$ can be evaluated:

$$F_L = B_L l l; \ [F_L] = N$$ \hspace{1cm} (6)

For an arc length of $l = 0.005 \text{ m}$ the deflecting force $F_L$ on the atmosphere is:

$$F_L = 0.0133 T * 500 A * 0.005 \text{ m} = 0.033 N$$ \hspace{1cm} (7)

Inert or forming gas is used to improve the control of the arc during the welding process. Benefits are advanced ignition behavior and electric conductivity, stabilization and relighting of the arc, short circuit resolution and protection of the welding zone. In order to calculate possible variances of the force $F_L$ under realistic weld conditions the force $F_L$ was determined for argon, helium and carbon dioxide as gases. Because only the susceptibility $\chi_m$ of argon is known, the permeability $\mu_r$ can be determined with:

$$\chi_m,Ar = \mu_r - 1$$ \hspace{1cm} (8)

For argon with $\chi_m,Ar = -19.7 \times 10^{-6}$ the permeability is

$$\mu_r = -19.7 \times 10^{-6} + 1 = 999980.3 \times 10^{-6}$$ \hspace{1cm} (9)

and the magnetic flux density results to

$$B_L = 4\pi * 10^{-7} \frac{Vs}{Am} * 10610.33 \frac{A}{m} * 999980.3 \times 10^{-6} = 13.334 \times 10^{-3} \text{ T.}$$ \hspace{1cm} (10)

The force $F_L$ results to:

$$F_L = 13.334 \times 10^{-3} \text{ T} \times 500 A \times 0.005 \text{ m} = 0.033 N$$ \hspace{1cm} (11)

As seen in these calculations, the effect of the permeability $\mu_r$ of the respective gases on the force $F_L$ is very small or even not existing. Equivalently the permeabilities of helium and carbon dioxide are calculated as following:

$$\mu_{r,He} = -1.9 \times 10^{-6} + 1 = 9999981.1 \times 10^{-6}$$ \hspace{1cm} (12)

$$\mu_{r,CO_2} = -1.2 \times 10^{-6} + 1 = 999999.9 \times 10^{-6}$$ \hspace{1cm} (13)
According to only minimal variations of permeability $\mu_R$, the magnetic flux density $B_L$ and force $F_L$ are:

$$B_{L,He} = 4\pi \times 10^{-7} \frac{V_s}{Am} \times 10610.33 \frac{A}{m} \times 999998.1 \times 10^6 = 13.333 \times 10^{-3} \text{T}$$

(14)

$$B_{L,CO_2} = 4\pi \times 10^{-7} \frac{V_s}{Am} \times 10610.33 \frac{A}{m} \times 999999.9 \times 10^6 = 13.333 \times 10^{-3} \text{T}$$

(15)

$$F_L = 13.333 \times 10^{-3} \text{T} \times 500 \text{A} \times 0.005 \text{m} = 0.033 \text{N}$$

(16)

It is noticeable that tube geometry has no influence on the force. Factors of influence are tube distance, diameter of the arc and welding current. The arc diameter cannot be operated directly and is assumed to be 1.5 mm. This assumption has to be identified experimentally in the next project run.

The tube distance is assumed to be constant at 5 mm for further examinations. At closer distances short circuits occur by drop formation of the welding material. Deductively the only variable in calculations of the force $F_L$ is the welding current.

In figure 1 the force $F_L$ is represented in dependency of the welding current.

![Graph showing force $F_L$ as a function of welding current $I$](image)

Fig. 1: Force $F_L$ as a function of welding current $I$

*Calculation of the magnetic coil*

Preliminary considerations proved the coaxial arrangement of the coil elements as the most promising version. It guarantees a homogeneous magnetic field on the tube circumference (Fig. 2).
This implies that the magnetic field produced by the coils spreads as shown in Fig. 2. The coils are inversely poled. As a result, the magnetic flux lines coming from both sides and meeting in the weld gap get concentrated at this point and do not overlap. As a consequence, the magnetic field density rises and the flux lines escape to the outside rotation-symmetrically and return around the respective coil. The preliminary calculation of the magnetic coils took place analytically to define the dimension of the coils and to produce a magnetic field that is strong and stable enough. Therefore, it is crucial to be able to describe the interactions of welding current, material, applied magnetic field, force on the arc and its course of movement as accurately as possible.

To deflect the arc, the magnetic field has to feature an ideal size and orientation. The generation of the magnetic field is realized with coils. The force acting on the arc has to be larger than $F_L$.

\[ F_L = 0.033 \, \text{N} \] (17)

Due to the fact that magnetic fields can only be calculated accurately inside of a coil, the induced force $F_S$ is multiplied by a coefficient of safety $S = 3$ and called $F_{S,\text{min}}$.

\[ F_{S,\text{min}} = F_S \times S = 0.033 \, \text{N} \times 3 = 0.099 \, \text{N} \] (18)

With $F_{S,\text{min}}$ and equations 3/5/7, the number of windings $n_S$ can be determined through:

\[ n_S = \frac{F_{S,\text{min}} \times 2\pi r}{\mu_0 \mu_r l_S^2 i_S} \] (19)

The coil current $i_S$ is assumed to be 3 A, the length of the coil body (winding length) is $l_S = 40 \, \text{mm}$ and the radius $r$ of the coil conductor is 0.4 mm.
\[
S = \frac{0.099 \text{ N} \cdot 2\pi \cdot 0.004 \text{ m}}{4\pi \cdot 10^{-7} \text{ T} \cdot \text{m} / \text{A} \cdot (3 \text{ A})^2 \cdot 0.04 \text{ m}} = 550
\]

With values as given above the number of coil turns has to be 550 to generate a deflecting force of 0.099 N.
If a security of \(S = 3\) does not suffice to actuate the arc in a controlled way, an adaption with adjustable coil current is possible.

**Calculation of the coil voltage**

From the calculation of coil windings the number of windings \(n_{S, \text{min}} = 550\) and coil current \(I_S = 3\) A are already known. For a body length of 40 mm and a diameter of the coil wire of \(d_D = 0.87\) mm (with protective coating), 43 windings per layer can be produced. Every layer has an increasing coil diameter of \(2^*d_D\). Applying a commercial copper wire of 100 m length 16 layers can be achieved.

The conductor length \(l_D\) results from:

\[
l_D = \sum_{n=1}^{16} 43 \cdot 2\pi \cdot (r_0 + [n - 1] \cdot d_D) = 99.77 \text{ m}
\]  

(20)

With a conductor length of \(l_D = 99.77\) m and the specific resistance of the copper conductor \(\rho_{\text{cu}} = 17.3 \cdot 10^{-3} \frac{\Omega \cdot \text{mm}^2}{\text{m}}\) the coil resistance can be calculated to:

\[
R_S = \rho_{\text{cu}} \cdot \frac{1}{A} = \rho_{\text{cu}} \cdot \frac{1}{\pi \cdot r_0^2} = 17.3 \cdot 10^{-3} \frac{\Omega \cdot \text{mm}^2}{\text{m}} \cdot \frac{99.77 \text{ m}}{\pi \cdot (0.4 \text{ mm})^2} = 3.43 \Omega
\]  

(21)

With the coil resistance and coil current, the coil voltage can be calculated by Ohm’s law:

\[
U_S = R_S \cdot I_S = 3.43 \Omega \cdot 3 \text{ A} = 10.3 \text{ V}
\]  

(22)

The calculations are based on acceptances, idealized considerations (magnetic field, coil voltage) and basic formulas. They are designed for one distinct geometry (coil body, coil conductor). However, these are irreplaceable for a fundamental determination of parameter fields. Therefore, components for expanded application parameters (e.g. higher coil voltage) are selected or adapted additionally.

**Distribution of the magnetic fields**

Inside of a coil there is a homogeneous magnetic field. Accurate statements about the magnetic field are possible only for this area. In fig. 3 it can be seen that the magnetic field
within the coil is homogeneous and inhomogeneous outside of the coil. This has to be determined in further experiments.

![Image of coil magnetic field lines](image)

**Fig. 3: Example of coil magnetic field lines [2, 3]**

*Weldability of the drill pipe*

The drill pipe materials are construction steels (low-alloyed steels), lightly modified in their chemical composition. The weldability of structural steels first of all depends on the carbon percentage in the material. This is safe up to a carbon concentration of $C \leq 0.22\%$. The carbon percentage of Coiled-Tubing materials is at most 0.15\% C. Therefore, the weldability is to be classified as unproblematic. For the first welding tests a structural steel P235GH and for the following experiments, a API J55 drill pipe material are available.

**WP 1: IFW: Study of the Process**

For the connection of drilling tubulars by welding, a plane surface of the contact area has to be provided. For this purpose the tubulars have to be machined. Thus, experimental examinations for the identification of suitable machining strategies have been conducted. Aim of the experimental examinations is the conceptual comparison of the material removal processes applied on drilling tubulars. Therefore, technological cutting experiments on a laboratory scale have been carried out to evaluate the required energy, the resulting cutting forces and the chip shape of the applied machining processes. Milling and turning have been selected as machining processes for the preparation and finishing of the welding seam (Fig. 4) in agreement with the project partner. Axis parallel turn-milling and orthogonal turn-milling are investigated in detail.

At the beginning of the machining experiments, the tube material QT-800 was characterized analytically in terms of its mechanical and chemical properties. Based on similar physical properties to the mild steel C45, comparable cutting process parameters have been selected for the machining of QT-800 with coated (AlTiN) carbide cutting tools. For machining C45 AlTiN is a typical tool coating.
**Axis-parallel turn-milling**

Within the examinations the axis-parallel turn-milling was initially examined to identify technological process limits for the concept of the machining device. A 4-axis milling machine Heller MCi 16 was used. All experiments are carried out without cooling lubricant. The feed motion of the cutting tool is generated by the machine table on which the drilling tubulars were clamped. The cutting forces were measured with a Kistler 9123CQ05 dynamometer. The used solid carbide milling tool with TiAlN coating has a diameter of $D_{WZ} = 8$ mm and a number of teeth of $z = 6$. The geometrical cutting parameters, depth of cut $a_p$ and cutting width $a_e$ were chosen according to the manufacturer's recommendations for mild steel ($a_p = 1$ mm, $a_e = 4$ mm). The cutting speed $v_c$ was set to 120 m/min. The feed rate per tooth was $f_z = 0.36$ mm. These parameters are the initial values for the technological examinations.

In the following examinations the cutting speed was varied in the range of $v_c = 100 - 130$ m/min. The feed rate per tooth remains constant at $f_z = 0.36$ mm.

For the examined process parameters, process forces at a reasonable level (100 - 250 N) result. Here a steady state of the machining process is resulting. To determine the required energy, the cutting power $P_c$ was calculated. The cutting power results from the cutting force and cutting speed according to Eq. 23. Figure 5 presents the progress of the cutting force $F_c$ and the calculated cutting power $P_c$.

$$P_c = F_c \cdot v_c$$  \hspace{1cm} (23)

Thereby, a typical progress of the cutting forces for machining of steel appears. With increasing cutting speed the cutting forces decrease. Consequently the cutting power $P_c$
decreases as well. This can be attributed to increasing temperatures in the cutting zone, due to the changing cutting speed, which promote the chip formation.

![Fig. 5: Process forces and cutting power for axis-parallel turn-milling](image)

The generated surface roughness was measured by a Mahr Perhometer PGK with tactile stylus method. The axis parallel turn-milling process generates low values of the average maximum height of roughness with $R_z \leq 10 \mu m$. The measured distance of the groove was close to the value of the feed per tooth with $f_z = 0.36 \text{ mm}$. The achieved surface quality enables the melting of two tubulars. The results can not be transferred directly for turning or axis-ortogonal turn-milling. Therefore further examinations were conducted.

The chip geometry was also analyzed for the machining process. For each parameter combination very short discontinuous chips were generated. The short discontinuous chips can easily be taken away by the cooling lubricant and can be rated as uncritical for the machining process. This fact should be taken into account for the construction of the machining device.

In order to rate the process forces for cutting steel QT-800 and to give a forecast for future machining operations, they are calculated by the Kienzle method for steel C45E. The same process parameters were chosen and were compared to the experimentally determined cutting forces of QT-800. Therefore, the medium chip thickness $h_m$ for the axis-parallel process has to be calculated. The chip thickness for milling depends on the operation direction angle $\phi$ and is consequently not constant ($h=f(\phi)$, Fig. 6).
For the determination of the resulting forces and the cutting power a medium chip thickness is assumed, which can be calculated by Eq. 24.

$$h_m \approx \frac{360^\circ}{\pi \cdot \Delta \phi} \cdot \frac{a_e}{D} \cdot f_z \cdot \sin \kappa$$  \hspace{1cm} (24)

However, not all teeth of the milling tool are in contact at the same time, therefore an average cutting force for each tooth has to be calculated (Eq. 25). This can be referred to the teeth in contact by the usage of the angle $\Delta \phi$.

$$F_{cm} = F_{cm,x} \cdot z_e = F_{cm,x} \cdot \frac{\Delta \phi}{360^\circ} \cdot z$$  \hspace{1cm} (25)

For the calculation of the average cutting force the calculation method of Kienzle (Eq. 26) was used.

$$F_{cm,x} = k_{c1,1} \cdot b \cdot h_m^{1-m_c}$$  \hspace{1cm} (26)

The material constants $k_{c1,1}$ and $m_c$ are the principal values of the specific cutting force $k_c$. For the material C45E it can be calculated according to Eq. 27. The comparison of the measured cutting forces with the predicted forces, which were calculated by means of the Kienzle-method, shows that the process cutting forces at the cutting speed $v_c = 120 \text{ m/min}$ are slightly smaller than the predicted ones (Fig. 7).
\[ k_{c1,1} = 1475 \frac{N}{mm^2} \text{ und } m_c = 0.2119 \]  

(27)

Fig. 7: Comparison of predicted and measured cutting forces

Kienzle’s calculation method and the usage of the specific values for steel C45E enable the forecast of the cutting forces, which can be applied to other cutting processes. For the axis-parallel turn-milling good machinability regarding chip formation and surface quality was reached.

This reveals, that for the machining of the QT-800 the recommended process parameters \((v_c \geq 120 \text{ m/s})\) and the cutting force prediction with the Kienzle-method can be applied. Here, an overestimation of the process force is resulting, which is non-critical for the machining process. The Kienzle-method is also applicable for the turning and orthogonal turn-milling. Thus, adequate process parameters for the other selected manufacturing processes can be derived. Furthermore, the predicted cutting forces and rates can be used for the design and conception of the cutting system. This indicates an adequate machinability for the QT-800 in order to prepare and finish the joint of the coiled tubes.

**Turning**

The influence of the process parameters on the resulting surface quality of the machined tubulars was examined accordingly in experimental turning investigations. Thereby, detailed experiments were carried out to identify process parameters that guarantee a stable and productive machining process. In this context the specific cutting force \(k_c\) for QT-800 was
calculated for turning to determine cutting forces and power. For the experimental investigations a cutting insert made of KC9125 was used. With this tool, the machining of mild steel in a roughing and finishing operation is possible. The pivotable fixing of the rectangular shaped tool enables the external machining, as well as face machining and chamfering. Turning is also suitable for machining with interrupted cut, such as the machining of tubulars with welding joint. A chip breaker geometry supports the chip formation.

The experiments were taken out based on a fully fractional designed experimental plan. The cutting speed was varied in six steps between \( v_c = 50 - 500 \) m/min (50, 100, 150, 200, 300, 500). The feed rate was set to \( f = 0.1 \) mm/U and \( f = 0.25 \) mm/U. The depth of cut was \( a_p = 2 \) mm. This experimental design was used for face machining and chamfering. The chamfer is realised with an angle of 40°. All experiments are carried out without cooling lubricant. The cutting force, the force in feed direction and the passive force as well as the chip formation and the surface roughness are used for process evaluation. During machining, the cutting forces are measured and will be used for the calculation of torque and power. The resulting force progression is illustrated in figure 8. With increasing cutting speed \( v_c \) a reduction of the cutting force appears. From a value of \( v_c = 200 \) m/min the cutting forces approximate a limiting value. This progress can be explained by increasing process temperatures, which influence the chip formation positively. The cutting force \( F_c \) has the highest values and the passive force \( F_p \) the lowest values. Increasing the feed rate raises the force level.

![Figure 8: Process forces for face turning](image)

**Fig. 8:** Process forces for face turning
The generated chips of the face cutting operation are illustrated in figure 9 for both feed values. For the feed $f = 0.1 \text{ mm}$ cylindrical-helical chips result for the cutting speed $v_c = 100 \text{ m/min}$, which fade to ribbon chips ($v_c = 500 \text{ m/min}$). This chip geometry is classified as unfavourable for turning, because the chips can wrap around the workpiece. For a feed of $f = 0.25 \text{ m/min}$ cylindrical-helical chips are generated up to a cutting speed of $v_c = 300 \text{ m/min}$ which can be rated as suitable for the machining process.

**feed speed $f = 0.1 \text{ mm}$, depth of cut $a_p = 2 \text{ mm}$, face turning**

![Chip formation for turning](image1)

**feed speed $f = 0.25 \text{ mm}$, depth of cut $a_p = 2 \text{ mm}$, face turning**

![Chip formation for turning](image2)

**Fig. 9:** Chip formation for turning

The measured surface roughness values increase when raising the feed. The measured maximum height of roughness values for the feed $f = 0.1 \text{ mm}$ as well $f = 0.25 \text{ mm}$ are lower than $R_z = 10 \mu\text{m}$. For a feed of 0.5 mm a maximum height of roughness values greater than $R_z = 50 \mu\text{m}$ was measured. Furthermore, the measured maximum height of roughness $R_z$ correlates with the calculated theoretical roughness $R_{th}$. The theoretical roughness $R_{th}$ can be calculated by the usage of the variables corner radius $r_c$ and the feed $f$.

Experiments for chamfer turning were conducted and reveal the same process behavior as for face turning. The process forces show the same characteristic progression as the forces for face turning (fig. 10). In a direct comparison to face turning, they are on a lower level.

For a feed of $f = 0.1 \text{ mm}$ and a cutting speed of $v_c = 300 \text{ m/min}$ unfavourable long cylindrical-helical chips result. When exceeding the value $f = 0.25 \text{ mm}$ at any cutting speed, unfavourable chip geometries result. These chips range from long cylindrical-helical chips ($v_c = 50 \text{ m/min}$) to ribbon chips ($v_c = 500 \text{ m/min}$). A consideration of the surface roughness is not needed, because the chamfers are not a contact area for welding.
For a fast preparation of the tubulars welding area, the cutting speed \( v_c \) and the feed \( f \) are the main influential variables. The higher these variables are chosen, the faster the machining operation is completed. Limits of the process are the chip formation and the generated surface roughness of the welding spot. For the surface roughness the feed rate of \( f = 0.25 \text{ mm/min} \) is the limiting boundary. At higher feed rates, roughness values greater than \( R_z = 10 \mu \text{m} \) result. For the chip formation during face turning a cutting speed of \( v_c = 200 \text{ m/min} \) and a feed rate of \( f = 0.25 \text{ mm} \) are suitable. For turning of chamfers a cutting speed of \( v_c = 200 \text{ m/min} \) and a feed rate of \( f = 0.1 \text{ mm/min} \) are acceptable.

**Axis-orthogonal turn-milling**

For examinations of the axis-orthogonal turn-milling process the feed per tooth was increased to a maximum of feed per tooth \( f_z = 0.12 \). The tool cutting speed was constant (\( v_c = 120 \text{ m/min} \)). In case of increasing the feed \( f_z \), a linear rise of the process forces was measured. The calculated specific force \( F_{cmz} \) is nearly identical with the cutting force \( F_c \) (fig. 11). The progression of the generated surface roughness values is not linear like the progression of the measured process forces (fig. 12). Up to a feed per tooth of \( f_z = 0.8 \text{ mm} \) a nearly linear progression appears up to \( R_z = 5.6 \mu \text{m} \). For a further increase of the feed per tooth to \( f_z = 1.0 \text{ mm} \), the progression of the measured roughness values flattens and reaches a maximum of \( R_z = 5.7 \mu \text{m} \). Another increase to \( f_z = 0.12 \text{ mm} \) results in a lowering of the
roughness values to $R_z = 4.7 \, \mu m$. The calculation of the theoretical roughness $R_{th}$ deviates noticeably from the machined surface roughness.

**Fig. 11:** Process forces for axis-orthogonal turn-milling

**Fig. 12:** Surface roughness for axis-orthogonal turn-milling
The process load is significantly smaller than for turning but higher than for axis-parallel turn-milling. The generated surface roughness of the welding spot (< Rz = 6 μm) is consistently better than after turning. Furthermore, axis-orthogonal turn-milling offers advantages to compensate tool wear by shifting. Also axial positioning inaccuracy can be compensated in the same way. The chip geometry can be rated as uncritical, similar to the axis-parallel turn-milling process, because only short chips were generated. The limits of the axis-orthogonal turn-milling are currently not reached for the used tool concerning topography, chip geometry and process forces.

**WP2/3 IW- Construction, assembling and startup of a MIAB welding test rig / Determining and optimization of material characteristics:**

WP2.1: The individual assembly groups were designed and the MIAB test rig was constructed based on calculations in WP1.

*The FEA simulation software ANSYS™*

In parallel to the production part, magnetic field simulations of the coil system have taken place using the ANSYS™ software. The simulation minimizes the development effort and supports it. The qualification of the results took place basing on measurements with a magnetometer on real component parts.

For the exact coil design, an analytical calculation is not sufficient, since statements are only possible in the homogeneous field region. The field orientation and field strength can only be studied and visualized sufficiently with a magnetic field simulation based on the finite element analysis (FEA). The FEA is a widely used, numerical calculation method that is used to describe and check physical phenomena mathematically. At the Institute of Materials Science ANSYS is already successfully used for the simulation of steel quenching behaviour. It is a so-called general-purpose program that covers a wide range of applications. Its applicability is to be investigated. The results from the magnetic field simulation contain the visual representation of the orientation and the field strength of the coils.
Figure 4 shows the concept's realization with the preprocessor. It was modeled only one half of the geometry. The y-axis represents the axis of rotation of the axial symmetry modeled elements. All results presented in this chapter are to reflect on this axis to visualize a complete structure section. Fig. 14 shows an enlarged detail of the model with already meshed elements.

The coils poled inversely. This serves to concentrate the magnetic field between the pipe-joint surfaces and to increase the magnetic flux density. The model has been rotated by 90°. This is of great importance for the solver. For a correct calculation of the results, the vertical axis (y-axis) must be defined as a rotation axis when using axisymmetric element properties in a 2D analysis with ANSYS. To rotate the 2D model around the symmetry axis, and thus to simulate a real 3D geometry, it was thus possible to generate only half of the 2D model. For
this purpose all related elements were modeled with axially symmetric properties. In table 1, the output parameters are displayed, which were used for the model generation.

<table>
<thead>
<tr>
<th>Parameter /Variable</th>
<th>Value</th>
<th>Abbreviation</th>
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<tr>
<td>arc length</td>
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Tab. 1: FEA model parameters

*Magnetic flux lines and magnetic vector potential*

Figure 6 shows the model's arrangement of magnetic flux lines, and an enlarged detail in the region of interest between the tube and coil end faces.

Inside the tubes, the low resolution can be seen. However, already here the course of the magnetic flux lines can be detected. They are attracted and absorbed by the tubes acting like coil cores and pass inside the tubes densely crowded towards the center, leaving the end surfaces again. Symmetrically to the reflection axis between the two coils, the magnetic fields repel in opposite directions. Then they extend outdoors around the coils and return back to the tube's rear sides again. Inside the tubular components area, the concentration of the vector potential is negligible. This is due to the coil cores effect of the tubes with high magnetic permeability which absorb the magnetic field.
Fig. 15: Flux lines of the FEA model

Fig. 16: Magnetic potential of the complete model

The graph on the right side of fig. 16 is shown in an adapted resolution and shows a greatly enlarged section of the arc area. In the zoomed view the components to be welded are shown as white frames. One can clearly see the exit of the flux lines from the tubular end faces and recognize the change in direction and the straight-line path to the outside.

**Magnetic flux density**

The distribution of the magnetic flux density was calculated for this concept too. The vector course in fig. 17 can be seen for the overall model.
It is clearly visible that the magnetic flux density amount increases within the components and decreases after emerging the air space. The area in the arc region is enlarged in fig. 18.

It clearly shows the desired course of the magnetic field vectors straightly crossing the arc from inside out. The emerging vectors exiting perpendicularly out of the pipe ends get deflected at 90° already within a distance of about 1 mm. The orientation of the magnetic vectors in the arc region can be calculated from fig. 18. For presenting the relations in the arc region more accurately, the magnetic flux density amounts have been evaluated overall and in radial direction according to the arrangements shown in fig. 19.
Fig. 19: Symmetrical base model of magnetic field lines and orientation in the weld gap

Three virtual measurement points have been moved in the welding gap (fig. 19). The values of magnetic flux density in sum ($B_{SUM}$) and in radial direction ($B_x$) were applied over the path (fig. 20). Using the analytical calculations (WP1) and the FEA-calculations of inhomogeneous magnetic fields based on ANSYS it was possible to develop the required magnetic field formers for the MIAB welding process.

Fig. 20: Analysis of the magnetic flux density in the welding gap

The fundamental construction of the machine consists of the coil system, the work holding device, the hydraulic moving unit, the welding current source and the measuring and regulating systems. Furthermore the electric connections and hydraulic pipes were adapted and it was made sure that the assembly groups are isolated thermally and electrically from each other. The test rig is shown in figure 21.
WP3.1: The welding tests of the first MIAB rig version (WP2.1) showed significant displacement and lack of fusion in the weld (fig. 23). Figure 23 illustrates typical microstructure composition of the welded joints. The welding seam has a martensitic structure with shares of bainite. The heat affected zone and the base material are ferritic / perlitic. An H₂-analysis of the weld has been performed to exclude possible hydrogen embrittlement by the shielding gas. The results of the studies show no indicating values for possible embrittlement. The measured values of the base material even exceed that of the welds (tab. 2).
**Fig. 23:** Welding parameters and cross-section structure image of the weld seam

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<th>weld seam</th>
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<td>specimen 1</td>
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Tab. 2: H$_2$-analyse of base material and weld seam, material P235GH

**WP2.2:** Based on the results of WP3.1, a development of the experimental test rig in WP2.2 was carried out. Focuses were on the optimization of the clamping system (offset minimization), removing the oxide layer or lack of fusion in the weld zone through specific formation of the shielding gas, increasing the compression rate and improving the operability. Figure 24 shows the components of the test rig after implementing the design. In tests, an offset of the welded connection between the tubes was observed. Therefore, an additional clamping at the respective pipe ends with fixed and floating bearing was installed to the existing fixture.

For further investigations, a welding chamber that encapsulates the weld zone is used. This allows an inert gas atmosphere during the welding process.
Fig. 24: Assembly parts in focus of optimization efforts

The installation of a pressure accumulator to the hydraulic valve block and the re-regulation of the control system allowed the enhancement of the compression rate by a factor of eight. For optimum control of the hydraulic system, the controller of the company Doli GmbH was adapted. This can be controlled by programmable flow software.

A more efficient welding power source with up to 1000 A welding current and the time control of different welding currents could be realized by adapting a programmable welding power source from EWM, Tetrix. The system provides the ability to deposit developed programs for the welding job (tube geometry and material) and retrieve.
**WP3.2:** In this work package the investigation of the implemented design changes in WP 2.2 have been made. Another point is a suitable formation of preventing scalings and notches in the connection. For the formation a gas ring or a welding chamber was used.

**Fig. 26:** Formation with shielding-gas ring
The shielding gas was initiated from outside or inside. The results of the welds are shown in fig. 28 – 30. Here welding with welding chamber and inner formation have achieved best results. It prevents scaling on the surface and ensures a smooth arc rotation. Other advantages of this shielding gas formation show the macrosection images in unetched condition (fig. 30). It becomes clear that welding with process chamber prevents oxides in the joint zone and possible notch effect can be minimized by an unfavorable weld shape.

Fig. 28: Results of the welding tests, material J55
Metallographic examinations of the weld also show a weld without fusion defects and inclusions (fig. 31). The heat affected zone has a ferritic-pearlitic structure. The weld has a mixed microstructure of ferritic-pearlitic and bainite-martensite structure. The weld bead is primarily martensitic.
Fig. 31: Structional image of the weld seam, etched with 2% HNO$_3$, material J55

Fig. 32: Microhardness test of the weld seam, Vickers HV0.2, material J55

The micro-hardness tests (Vickers) of welded joints show a basic hardness of 190HV0.2. The hardness of the weld in arithmetic average is at about 380HV0.2. The hardness values
scatter strongly and confirm the mixed structure already shown in the metallographic 
investigations in the weld.
For further experiments an automation of the welding process is planned. This ensures the 
reproducibility of results and transfer to the industrial application.

WP 2/3: IFW: Process selection an designing/ Qualification of the removal process 
and designing of a machine tool

Process selection
Based on the experimental investigations for turning and milling of the tubulars, a 
comparative matrix for possible machining processes was created. Closely followed by turning, 
the axis-orthogonal turn-milling was qualified for the machining of the welding zone. 
However, during turning the cutting speed is generated by the rotation of the workpiece. 
Therefore a standard turning process can not be applied to tubulars at the drilling location. 
For the examinations the cutting tool was rotated around the tubular. The axis-orthogonal 
turn-milling offers the highest fault tolerance for the positioning of the tool. This applies to the 
feed direction movement of the tool in axial directon as well as for the movement in radial 
direction. Both processes enable the machining of a plane surface, necessary for the welding 
of the tubulars. Nevertheless the generated surface roughness after turning was only slightly 
better than after milling. The examined machining processes according to DIN 8580 for the 
machining of the welding zone are rated by the most important criteria (table 3).

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Axis-orthogonal turn milling - Tool wear and process limitations
As already shown, the process limits of the axis-orthogonal turn-milling have not been 
reached. In order to verify the tested process parameter for several cuts, wear test with 25
cuts with an unused tool were conducted. The first 20 cuts were assumed for an average drill hole depth of 5000 m, whereby 10 tubulars with a length of 500 m were machined on both sides. Additional 5 cuts were performed for overrun. Here tools of different providers were tested to guarantee a robust process. A low priced tool (milling cutter 1) and a tool of the upper price segment (milling cutter 2) were used. At the beginning the maximum process parameters of the process study were used. In the following the feed was increased up to \( f_z = 0.2 \) mm. The used milling tool \((z = 6)\) showed a stable process behavior up to \( f_z = 0.16 \) mm. For \( f_z = 0.2 \) high process forces appeared as well as an unstable process run. The process forces for the feed rate \( f_z \) up to 0.16 mm were at a constant level at every cut. Figure 33 presents the progression of the measured process forces. For each parameter setting an unused tool was used.

**Fig.33 process force progression for 25 cuts**

For a feed per tooth of \( f_z = 0.12 \) mm the curve progression of the normal forces \( F_N \) for both tools were on a comparable level of 350 N. By increasing the feed per tooth to \( f_z = 0.16 \) mm a small deviation of 20 N appeared. With regard to the process load both tools are suitable. Subsequent to the 25 cuts, the cutting tool wear was examined. Hereby no wear marks were located. A further increase of the feed per tooth to \( f_z = 0.2 \) mm resulted in higher forces. For this feed the process forces increased in average above 1050 N for machining the welding seam (fig. 32). An unstable process behavior appears. Further investigations were carried out with cutting tools with \( z = 5 \) cutting edges. The feed per tooth \( f_z = 0.16 \) mm and \( f_z = 0.2 \)
mm were examined as well. The process and wear behaviour is comparable to the results with the cutting tool with $z = 6$ cutting edges.

![Graph showing normal forces]  

**Fig. 32** Normal forces relating to the wall thickness

To identify the influence of the wall thickness of the tubulars, tubulars with $b = 3$ mm and $b = 4$ mm wall thickness were machined. For a feed rate of $f_z = 0.12$ mm the normal process force is $F_n = 380$ N for $b = 4$ mm and for $b = 3$ mm the process force in average is $F_n = 300$ N. Increasing the feed per tooth to $f_z = 0.16$ mm causes a normal process force of $F_n = 500$ N for $b = 4$ mm and a process force of $F_n = 450$ N for $b = 3$ mm.

The examination of the generated chip geometry reveals a change from short and uniform chips for $f_z = 0.12$ mm to a short and irregular chip geometry with various chip thickness for $f_z = 0.16$ mm. This behavior also indicates a process limit. Metallographic examinations of the machined area show no significant structural change caused by the machining process.

So the used cutting tool is suitable for a feed up to $f_z = 0.16$ mm.
Design of a machine concept

Three concepts for milling machines have been designed by using methodical design. The first concept is shown in Fig. 33. The machine can be assembled to a handling device e.g. an "iron roughneck". The machine clamps at the coil and is decoupled from the handling device. The feed axis moves the tool to the workpiece. With means of the rotational device, the machine moves around the coil while milling it. With changeable tools it is possible to cut the coil and to machine the chamfer for the weld preparation and to remove the joint patch after welding. With changeable powered tools, either the axis parallel turn-milling (use of a changeable tool with right-angled drive) or orthogonal turn-milling can be conducted.

![First machine-concept](image)

Fig. 33 First machine-concept

In the second machine-concept, which is shown in Fig. 34 a separable welding machine is integrated into the z-axis of the stationary milling machine. The milling machine is able to perform axis-parallel milling for weld preparation as described above. To increase the productivity an additional b-axis was integrated to allow the pivoting of the milling tool. Therefore, only one spindle is needed and the two coils can be machined in one clamping. With this machine kinematic, cutting of the coil cannot be executed because the turning of the coil is not possible. To still enable the cutting of coiled tubing, a circular saw was integrated. This machine allows a very fast cutting of the coil if needed. After the weld preparation of the ends of the work-pieces with the milling tool, the welding tool is positioned between the ends of the coils and the new delivered coil is stationed for welding. The welding process is accomplished as described previously in this report. After welding, the hydraulic cylinders apply the necessary force for the completion of the magnetic arc welding-process. Afterwards, the welding tool is opened and positioned in its home position.
The third concept is shown in Fig. 35. In this concept, turrets with multiple powered tools are used. Each turret is moved by means of three linear axes and one rotation axis to position and orientate the tool to the workpiece. With different tools, cutting, removing the joint patch after welding and machining of the chamfers for weld preparation is possible. The figure shows the variant with four turrets whereby a synchronous machining of both ends of the coil is possible.

**WP 4 IW – Processoptimization and prototype production:**
The results of WP2 and WP3 will be implemented into the test rig. This can be used for a requirement profile of the prototype welding-rig.
The MIAB system consists of four main control components:
- Hydraulic unit (press force),
- Coil control (magnetic field),
- Welding parameters (welding current power source) and
- Inert gas control.

At timing of system components is required for the later application. This made possible by a master PLC control and programming of sequential control as well as signal processing. For the implementation a Siemens S7-200 controller was used. Programming of signal processing and the user interface were performed at the Institute of Materials Science. The operation of the touch panels consists of four sequential consecutive steps:

1. Task selection (single review of the components / welding test)
2. Entering the magnetic field shaper parameters,
3. Selection of welding program including an arc start monitoring,
4. Control of all launch conditions and release of welding (fig. 36).

With the implemented control it is possible to weld positive results of WP3.2 reproducible and ensure consistent quality (fig. 37).
**WP 5 IW – Validation and conceptual industrial realization:**

In this workpackage the results of the previous workpackage will be investigated critically. Critical elements of the machine for the industrial application are determined and approaches for further optimization are developed. Based on WP2 and WP3, the influence of main parameters could be identified and the weld quality can be optimized. In particular pressing speed, regulations of the gas composition and inert gas flow rates as well as temporal coordination of the four main system components (WP4) are important. The industrial classification of the different materials which are approved by API, further research is necessary. Here mechanical tests such as pressure / burst tests and torsion tests of the welded joint under temperature influence are required. The points above recommended to be developed with industry or in a research project after the projekt's ending.

An encapsulation of the weld zone is furthermore required, due to explosion risk on the rig. At IW the design of a welding process chamber was developed (fig. 38). This allows a transfer into industrial applications.
1.1.2.4 Project Plan

<table>
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1.1.3 Delineation of the project from other funded projects

At present at the Institute of Materials Science and at the Institute for Production Engineering and Machine Tools of the LUH no projects are executed which are connected with high performance drilling technology. The applied project is not affected by any planned or running projects.

1.1.4 References


1.1.5 Publications, reports and presentations of Project W5


