Master Thesis

Dissimilar welding of alloy 625 (casted) and alloy 617 (forged) using Electron Beam Welding

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Field of Study

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DANKE

Christof Großegger

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Nowadays the CO_2 emission problem and the global warming get more and more important. The main goal has to be to lower this down as much as possible.

The increase of fossil running power plants' efficiency is an important topic. To achieve this, it is necessary to increase steam pressure and temperature. For the used materials this is very challenging. At these high temperatures the only applicable materials due to the required creep resistance are the so-called nickel based alloys. Due to their high price, they are only used in those parts of the power plant, where they are really necessary.

The scope of this thesis was to investigate the weldability of a dissimilar weld joint, using electron beam welding (EBW). The two base materials were casted nickel based alloy 625 with forged nickel based alloy 617. For comparison another welding process was used. This was done using shielded metal arc welding (SMAW).

To investigate the joints strength, some mechanical tests were performed (tensile-, hardness-, notched-bar-impact test). The investigations on the microstructure were done using light optical microscope as well as scanning electron microscopy.

All the tests were done according to the standards ÖNORM EN ISO 15614-1 and ÖNORM EN ISO 15614-11.

The welding experiments stated out, that the EBW process is better suited for joining this dissimilar weld as the SMAW process. Nevertheless both processes would have passed all tests according to the welding procedure specification (WPS).

Heutzutage wird das CO_2 Problem und der globale Temperaturanstieg immer wichtiger. Das Hauptziel muss es sein diese Problematiken so weit als möglich zu reduzieren.

Die Erhöhung des Wirkungsgrades der mit fossilen Brennstoffen betriebenen Kraftwerke ist ein sehr wichtiges Thema. Um das zu erreichen ist es unabdingbar den Dampfdruck und die Dampftemperatur zu erhöhen. Für die verwendeten Materialien ist das aber sehr problematisch. Die einzigen Werkstoffe, die bei solchen Temperaturen hinsichtlich der erforderlichen Kriechfestigkeit noch eingesetzt werden können sind die sogenannten Nickel-Basis Werkstoffe. Aufgrund ihres hohen Preises werden sie aber lediglich in solchen Teilen des Kraftwerkes genutzt, wo sie auch wirklich gebraucht werden.

Das Ziel dieser Arbeit ist die Untersuchung der Schweißbarkeit der artfremden Schweißverbindung mittels Elektronenstrahlschweißen. Die beiden Grundmaterialien sind ein Nibas 625 Gußteil und ein Nibas 617 Schmiedeteil. Zum Vergleich wurde auch ein zweiter Schweißprozess untersucht. Dieser ist der konventionelle Elektrodenschweißprozess.

Zum Untersuchen der Festigkeit der Schweißverbindung wurden einige mechanische Untersuchungen durchgeführt. Diese waren Zug-, Härte- und Kerbschlagbiegeprüfung. Die Untersuchung der Mikrostruktur wurde mittels Licht- und zusätzlich mittels Rasterelektronenmikroskop durchgeführt.

Alle Untersuchungen wurden angelehnt an die Normen ÖNORM EN ISO 15614-1 und ÖNORM EN ISO 15614-11 durchgeführt.

Die Schweißversuche ergaben, dass zum Fügen dieser artfremden Verbindung der EBW Prozess besser geeignet ist, als der Elektrodenschweißprozess. Nichtsdestotrotz haben beide Prozesse die Anforderungen der Schweißprozess-Spezifikation (WPS) erfüllt.

1 LIST OF ABBREVIATIONS

A617	alloy 617 (Nibas 617)
A625	alloy 625 (Nibas 625)
AEG	Allgemeine Elektrizitäts-Gesellschaft
AW	as welded
BE-mode	backscattered electron - mode
CALPHAD	CALculation of PHAse Diagrams
CCD	charged coupled device
CEA	Commissariat à l' énergie atomique
EBW	electron beam welding
EDX	energy dispersive X-ray spectroscopy
HAZ	heat affected zone
HTGR	high-temperature gas-cooled reactor
HV	hardness Vickers
LOM	light optical microscopy
MATCALC	MATerials CALCulator
PT	penetration testing
PWHT	post weld heat treatment
pWPS	preliminary Welding procedure specification
RT	radiographic testing
SEM	scanning electron microscope
SMAW	shielded metal arc welding (arc welding by hand)
TCP	Topologically Close Packed
UT	ultrasonic testing
VAGT	voestalpine Gießerei Traisen
VT	visual testing
WPQR	Welding procedure qualification record
WPS	Welding procedure specification

2 INTRODUCTION

The use of advanced steam cycles in the future Advanced Ultra Super Critical (A-USC) coal-fired power plants, with steam temperatures up to 730°C, which will provide increase in efficiency and reduction of CO2 emission, has modified the profile of the materials utilized. In Figure 1: CO2 Emissions in power plants [2] the increase of efficiency and decrease of CO2 emissions can be seen. As temperatures in the hottest part of the steam cycle in the range of 700°C are above the designed temperature range for creep resistant steels, Ni-base alloys are considered as candidate materials for the most severely exposed components of the new generation of power plants. Due to their excellent long-term high temperature properties they have already been frequently used for small parts operating at high temperatures (engine parts in airplanes and gas turbines). However, production of large, thick walled components, needed for very thick steam piping connected to the steam turbine of A-USC power plants, is a very challenging task for both, the manufacturing technology and the material performance assurance.[1]

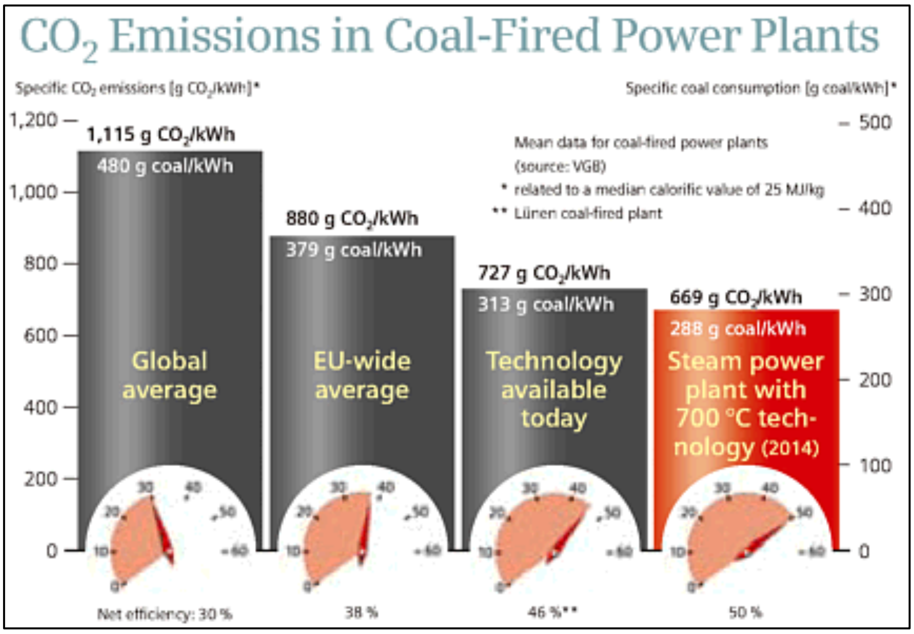


FIGURE 1: CO2 EMISSIONS IN POWER PLANTS [2]

The most critical parameter regarding the lifetime of the materials used in such power plants is the creep resistance.

3 AIM OF THE PROJECT

The demand for higher and higher operating temperatures of modern power plants can only be fulfilled by the use of especially creep resistance materials. Due to this requirement the use of nickel base alloys seems to be mandatory. These alloys guarantee also above 700° C an adequate creep resistance. Figure 2: Valve-body [3] shows exemplarily the part, where the material is used in the power plant.

FIGURE 2: VALVE-BODY [3]

Welding will stay the decisive joining technology in power plant production. The "voestalpine Gießerei Traisen" (VAGT) has already some experience with welding of nickel base alloys. In this thesis the focus is on the dissimilar welding of two different nickel base alloys. The first is the alloy 617, which is a forged part and the second is the alloy 625, which is a cast material. The alloy 617 for this investigation was purchased from the company ENPAR. The alloy 625 was produced at VAGT.

As part of this project two different sample welds had been performed. One was done via electron beam welding at the company probeam in Germany and the other one was done via shielded metal arc welding at VAGT. The goal is a characterization of the weld-ability based on the standard of EN ISO 15614-1.

4 LITERATURE REVIEW

This chapter provides a short theoretical background about the topics this thesis deals with.

4.1 CREEP BEHAVIOUR

Materials under stress behave different dependent on the present temperatures. Whereas the deformation at low temperatures is a function just of stress (e=f(s)), the deformation at high temperatures is a function of stress, time and temperature (e=f(s, t, T). This is due to thermally activated processes during the deformation.

At temperatures above 0,3 – 0,4 T_S [K] (T_S melting temperature) for calculations the time-dependent deformation and time-dependent cracking behavior have to be taken into account. In many cases, e.g. for gas turbines, the materials creep behavior limits the working temperature and therefor the efficiency. This is a motivation for the development of new alloys with a high creep resistance.

Two mechanisms of creep are distinguished. First the dislocations creep and second the diffusion creep.

The creep rate for both mechanism is limited due to the diffusion processes, whereas for both the Arrhenius-law is valid. [4]

$$k = A * e^{-\frac{E_A}{R*T}}$$

The mechanism for increasing of creep resistance and the underlying metal physics principles (prevention of dislocation movement and reduction of lattice diffusion) are nowadays well known. In the following the most important mechanisms for a creep resistance increase are listed:

- Reduction of diffusion in the matrix
- Solid solution hardening
- Carbide hardening
- Precipitation hardening
- Reduction of grain boundaries, e.g. coarse grains, directed solidification, single crystal

The lower the diffusion speed, i.e. the movability of atoms in the matrix, the higher the creep resistance. Due to their low diffusion coefficients nickel base alloys have an advantage in comparison to ferritic alloys. [5]

Increasing of creep resistance due to carbide hardening is often done via chromium carbides from the type M23C6 or via niobium, tungsten or molybdenum carbides from type M6C. Carbides in nickel base alloys can still be thermodynamic stable at temperatures above 1000°C, thus the strength increase is also available at high temperatures. Alloy 617 (2.4663) is a typical example for carbide-hardened material. [5]

4.1.1 CREEP TEST

According to DIN 50118

During creep testing a tensile test specimen is stressed at constant temperature and constant load. The observed strain is measured within a certain period. Figure 3: Creep test set-up shows the layout of a creep test facility.

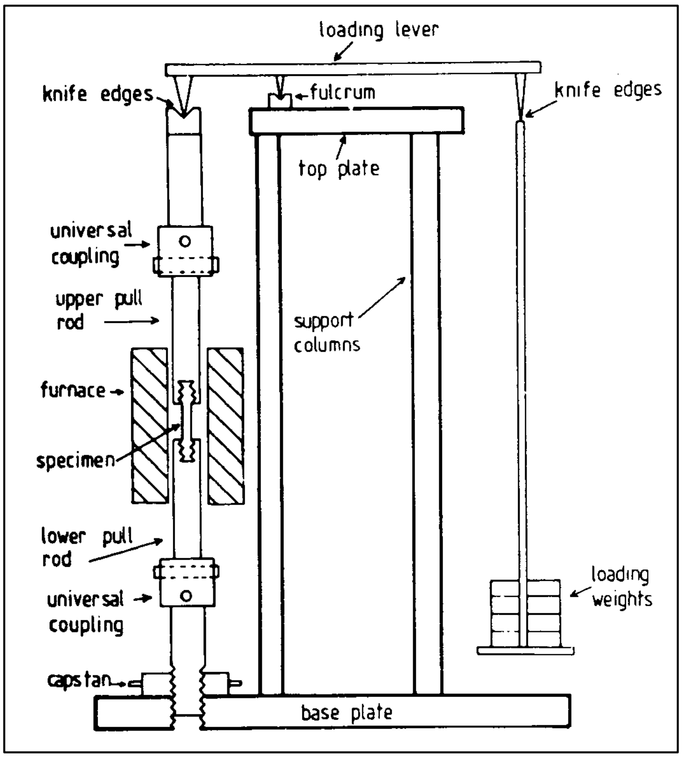


FIGURE 3: CREEP TEST SET-UP

The results of such tests are the creep rates. The curves show three distinguished areas: primary or transitional creep (first range); secondary or stationary creep (second range); and tertiary creep (third range). Figure 4 exhibits a typical creep curve.

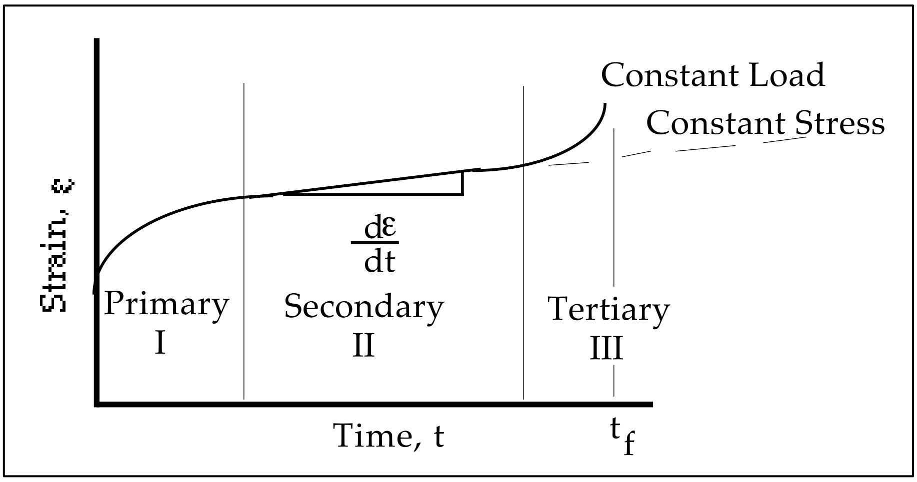


FIGURE 4: CLASSICAL CREEP CURVE

The first range, the primary creep, occurs at the beginning of the test. The creep rate in this range is not yet constant. The resistance against strain is increasing until the beginning of the second range. At the secondary creep range the creep rate is more or less constant. Therefor this area is called stationary creep. At the tertiary creep range the creep rate increases, whereas the specimens' cross-section decreases, due to the necking. If the test is progressed the specimen would break. The creep test is normally performed, to determine the minimum creep rate at secondary creep. This deformation has to be considered for the design face of constructions.

Similar to a creep test, a stress rupture test is performed. It is also done on a tensile test specimen under constant load and constant temperature. The difference is just the level of the load and the loading time. A stress rupture test is performed at higher loads and short times. Furthermore this test is always done till the rupture. It is used to determine the time until the rupture and strain.

4.1.2 PRIMARY CREEP

In the primary zone, the so-called primary transitional creep, the deformation speed is decreasing. This is due to the fact that the strain hardening outweighs the recovery. In solid solution hardened materials sometimes the opposite case can be observed, because the dislocation concentration increases without a decrease of the dislocation speed. Gradually a steady dislocation structure is built. Therefor the deformation speed has to be also steady.

The dislocations in the specimen are moving, so that no constant dislocation structure can be formed. Overall the parameters like dislocation structure; dislocation concentration and sub grain size remain constant.

The configuration of dislocations to each other does not belong to dislocation structure, because such a definition is senseless. A specimen dislocation structure would be different at any given moment. On the contrary it is a major role if sub grain boundaries are formed, or if the dislocations are homogenous distributed. Therefor these physical values are called parameters. [6]

4.1.3 SECONDARY CREEP

In the secondary zone the deformation rate is constant. If the experiment would not end due to inhomogeneous processes inside the sample, this could not lead to endless strains. Such processes are for example the building of creep pores. Every model, which is able to describe the stationary deformation speed, is also able to describe high strains. Due to the fact that micro-structurally there is no real stationary area, it is questionable if a model even has to describe high strains. [6]

4.1.4 TERTIARY CREEP

In the tertiary zone the creep rate -, in other words - the deformation rate is increasing. This increase is dependent on the specimens necking due to pore creation. Especially at tertiary creep the time is not directly influencing the creep curve. The range of tertiary creep occurs relatively fast, because of high deformation rates and therefor fast reached strains. For the creep curve the tertiary range can represent one third of the whole curve. In terms of lifetime the tertiary range will still just cover 1/20th of the whole lifetime. The position of the creep curves is influenced by the modification of temperature and stress. Both a temperature increase and a stress increase move the curve to a higher level. The shape stays the same, but the fracture strain decreases. [6]

4.2 RELAXATION CRACKS (STRESS RELIEF CRACKING)

In alloys having grain boundaries without precipitations, loads can primarily be reduced through local sliding at areas of particle-free grain boundary seams. The plastically deformation, which occurs before the fracture, is limited to areas of relatively simple deformable grain boundaries. The grains inside are hardened due to precipitation processes. At the environmental area of grain boundaries high stress-concentrations can occur, because the amount of grain boundaries at the total volume is low. The interaction between stress-concentrations and simple deformable grain boundaries leads to inter-crystalline separation. This appears brittle under macroscopic investigations, because the macroscopic deformations are low. Under microscopic investigations these segregations look like ductile along the grain boundaries. The reason for this is a structure with different local deformation abilities. The crack initiation starts, if the deformation resources of the particle-free grain boundary seams are varying. Therefor not the grain boundaries embrittlement is the reason of the segregation, but the high ductility of the grain boundaries in comparison to the grains' inside. Figure 5 shows a typical fracture surface of a relaxation cracking damaged specimen. [7]

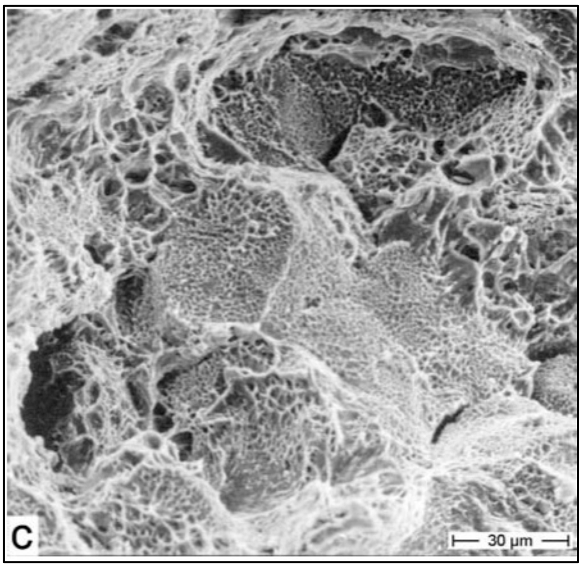


FIGURE 5: RELAXATION CRACK - FRACTURE SURFACE [7]

4.2.1 OCCURRENCE

Relaxation cracks occur at the coarse grain area of the HAZ after stresses relieve annealing. Sometimes damages occur during annealing between hot forming processes. In any case they are constrained to technological processes. By adequate temperature control at first precipitates are solved and due to reheating again precipitate. For this reason the cracking occurs.

To explain this phenomenon it has to be assumed, that during the pre-heating a stress reduction starts due to conversion from elastic to plastic deformation at creep conditions. This takes place in a matrix, where precipitates exist, providing a high thermal stability of the matrix (inside the grains). The grain boundaries crack already at macroscopic strains at levels of 0.2% due to high concentration of slide-processes. The level of heat treatment or welding residual stresses can be high enough to cause relaxation cracks. The main factor is the difference in strength of the grain boundaries and the matrix (grain inside). [7]

4.2.2 AVOIDANCE

Reduction of residual stresses due to welding: (no cross section or shape variation, no material mass accumulation, no excess weld material, low stresses due to heat). Regarding the materials structure a coarse grain size is detrimental for stress relief cracking. Annealing as a heat treatment reduces the susceptibility to cracking. Short delay time in the critical temperature range and high heating rates are also reducing the danger of crack initiation. As far as possible an crack-inspection (using magnetic particle inspection or dye penetrant testing) has to be done after welding such susceptible materials. [7]

4.3 ALLOY 617

Alloy 617, also designated as Inconel 617, UNS N06617, or W. Nr. 2.4663a, was initially developed for high temperature applications above 800°C. It is often considered for use in aircraft and land-based gas turbines, chemical manufacturing components, metallurgical processing facilities, and power generation structures. The alloy was also considered and investigated for the high-temperature gas-cooled reactor (HTGR) programs in the United States and Germany in the late 1970s and early 1980s. Alloy 617 retains some creep strength at temperatures above 870°C, the alloy has good cyclic oxidation and carburization resistance, and good weldability. It also exhibits lower thermal expansion than the most austenitic stainless steels and shows high thermal conductivity if compared to other alloy. It retains toughness after long-time exposure at elevated temperatures and does not form complex intermetallic phases that can cause embrittlement. [7]

4.3.1 ALLOYING ELEMENTS

In Table 1: chemical nominal composition of A617 (in weight%) [8], the nominal composition of alloy 617 between the min. and max. limits can be seen.

TABLE 1: CHEMICAL NOMINAL COMPOSITION OF A617 (IN WEIGHT%) [8]

C	Si	Mn	B	S	Cr	Mo
0.05-0.15	<1	<1	<0.006	<0.015	20-24	8-10
Ni	**Co**	**Ti**	**Fe**	**Al**	**Cu**	
>44.5	10-15	<0.6	<3	0.8-1.5	<0.5	

The required combination of creep resistance, corrosion resistance and stability restricts the possible options of alloys for high temperature energy systems to high-chromium, nickel-based solid solution alloys with relatively large and stable grain sizes. In nickel-based alloy 617, solution strengthening is primarily based on Co and Mo, while oxidation resistance is provided predominantly by Cr and Al. Under oxidizing conditions, Cr forms a dense oxide scale that protects the alloy from significant environmental degradation. In addition, the grain structure of 617 is stabilized after long-term exposure to elevated temperature by the formation of both inter-granular and intra-granular carbides Cr23C6 and Mo6C. The presence of carbides on the grain boundaries prevents boundary migration and contributes to creep resistance. The Cr-rich carbides are thought to precipitate primarily on the grain boundaries, while the Mo-rich precipitates are usually found within the grains matrix. Both inter-granular and intra-granular carbides are believed to affect the mechanical, creep and fatigue properties of the alloy. [9]

4.3.2 POST WELD HEAT TREATMENT (PWHT) ALLOY 617

In Figure 6: Time-temperature-transformation-diagram alloy 617 [10] it can be seen, which phases or precipitates can occur at different temperatures after certain time.

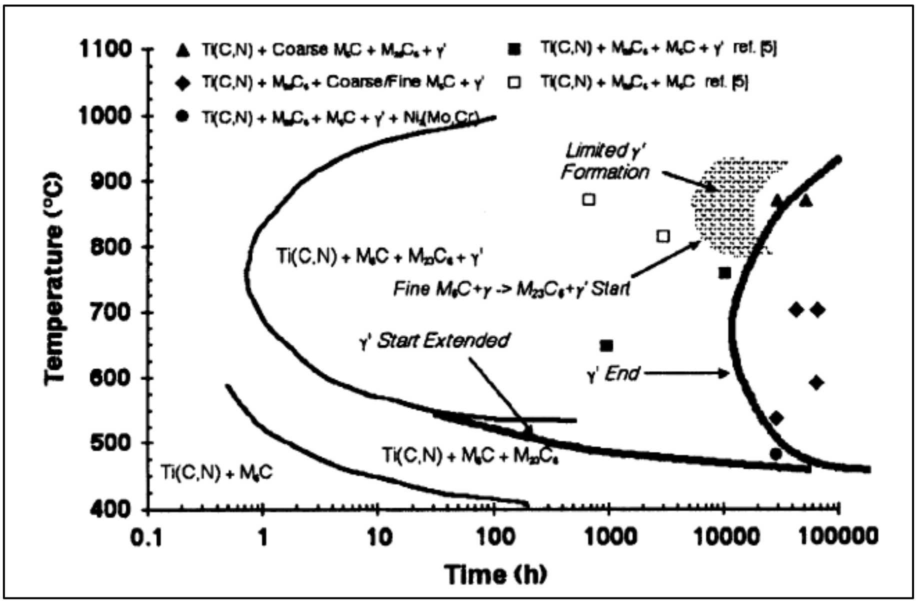


FIGURE 6: TIME-TEMPERATURE-TRANSFORMATION-DIAGRAM ALLOY 617 [10]

It is evident from the TTT diagram that various types of carbides formed in this alloy depend on various factors, like history of solidification, carbon concentration and heat treatment temperature, e.g. MC ('M' is mainly Ti), $M_{23}C_6$, ('M' is mainly Cr) and M_6C ('M' is mainly Mo).

Some alloys are classified as precipitation hardening. If a precipitation-hardening alloy is quenched, its alloying elements will be kept in solution, resulting in a soft metal. Aging an oversaturated alloy will allow the alloying elements to diffuse through the microstructure and form intermetallic particles. These intermetallic particles will nucleate and precipitate out of solution and act as a re-enforcing phase, thereby increasing the strength of the alloy. Alloys may age "naturally" meaning that the precipitates are formed at room temperature, or they may age "artificially" if precipitates are only formed at elevated temperatures.

4.4 ALLOY 625

The alloy 625 (A625) is a nickel-based super alloy with good mechanical properties, superior corrosion behavior and outstanding creep resistance. The microstructure of this material is cubic face centered and there are no phase transitions in the solid state. A625 is strengthened mainly by carbon, chromium, molybdenum and niobium. The high strength is achieved by solid solution hardening (Mo, Nb) and by precipitation hardening which is mainly derived from the metastable γ" phase [Ni3 (Nb, Al, Ti)]. Depending on the application of this material (high corrosion resistance or high creep resistance) different heat treatment is performed. For high temperature applications (T>600°C), where higher strength and better creep properties are required, the material is solution annealed at 1120°C to form Ni3 (Nb, Mo) phases. [11]

4.4.1 ALLOYING ELEMENTS

In Table 2: chemical nominal composition of A625 (in weight%) [12], the nominal composition of alloy 625 between the min. and max. limits can be seen.

TABLE 2: CHEMICAL NOMINAL COMPOSITION OF A625 (IN WEIGHT%) [12]

C	Si	Mn	P	S	Ni	Mo
<0.1	<0.5	<0.5	<0.015	<0.015	>58	8-10
Al	**Cr**	**Nb, Ta**	**Co**		**Ti**	**Fe**
<0.4	20-23	3.15-4.15	<1		<0.4	<5

4.4.2 PRECIPITATES AND PHASES

γ' - phase

This intermetallic phase (Ni3Al) is present in many nickel base alloys and is used as precipitation hardener. In the alloy 625 the γ' - phase plays a minor role, since the Al and Ti contents are low and the A625 tends to form the Nb-rich γ" - phase. [11]

γ" - phase

This γ" body-centered tetragonal phase (Ni3Nb) is metastable; it starts to be dissolve at 650°C. The precipitation kinetic of this phase is very slow, and results in a better weldability and a higher resistance against strain-age cracking during heat treatment. [11]

The γ" – phase in cast alloy 625 was analyzed in the Master Thesis of B. Bezzola (see [13]).

δ – phase

After some time the γ" - phase is transformed into the stable, orthorhombic ordered δ - phase. The δ-phase is undesirable because it is incoherent with the Ni matrix and therefore not an effective strengthener. In addition, it leads to embrittlement. This behavior results in a reduced creep resistance. [11]

The δ – phase in cast alloy 625 was analyzed in the Master Thesis of B. Bezzola (see [13]).

Laves phase

This is a TCP (Topologically Close Packed) phase with a nominal stoichiometry of A2B ((Cr, Fe, Ni) 2 (Si, Ti, Nb, Mo)), which is hard and brittle. This phase causes a reduction of the solid solution hardening elements Cr, Mo and Fe in the matrix and leads to a reduction in mechanical strength. In further consequence the reduction of Cr and Mo in the matrix can reduce the corrosion resistance drastically. Therefor the formation of the Laves phase should be avoided. [14]

MX

The MX particles have a cubic face centered crystallite structure and are primary precipitates from the melting. Two sorts of this primary precipitates exist, the Ti- rich carbon-nitrides and the Nb- rich carbides. The Ti- rich carbon-nitrides precipitate soon from the melting. Considering the high diffusion speed at this temperature level, less big and blocky particles are built. The Nb-rich carbides are formed at the end of the solidification and can be found in inter dendritic regions along grain boundaries. [14]

$M_{23}C_6$

This carbide has a complex cubic structure. Its main component is Cr, but it can be substituted by Fe, Ni, Co and Mo by approximately 30%. $M_{23}C_6$ carbides normally precipitate during a post weld heat treatment or during service operations between 760 and 980 °C. The precipitates are formed at grain boundaries, twin boundaries or stacking faults. Fine, single $M_{23}C_6$ precipitates at grain boundaries improve the creep resistance, due to the prevention of grain boundary sliding. [14]

M_6C

The M_6C carbides are mostly built at Mo- rich areas. Considering the distinct segregation behavior of Mo, this carbides can be formed at Mo- rich inter dendritic areas as well as at grain boundaries during the solidification. In the solid state this M_6C carbides precipitate at temperatures between 815 and 980°C. Above 1000°C the carbides are not stable anymore and turn into MX particles. [14]

M_3B_2

Boron as alloying element increases the creep resistance. In combination with other elements like Mo, Nb, Ti, Cr, Ni or Co, it forms borides called M_3B_2 at the grain boundaries. These borides are hard and are building a grain boundary solidification. Boron tends to segregate, thus the M_3B_2 precipitate at low temperatures. Boron increases the grain boundaries wetting so that the risk of hot cracking increases, too. In alloy 625 the boron concentration is low, but due to weld penetration and dilution a little amount of boron in the weld metal is possible. [15]

4.4.3 POST WELDING HEAT TREATMENT (PWHT) ALLOY 625

In Figure 7: Time-temperature-transformation-diagram alloy 625 [16] it can be seen, which phases or precipitates can be formed at different temperatures after certain time.

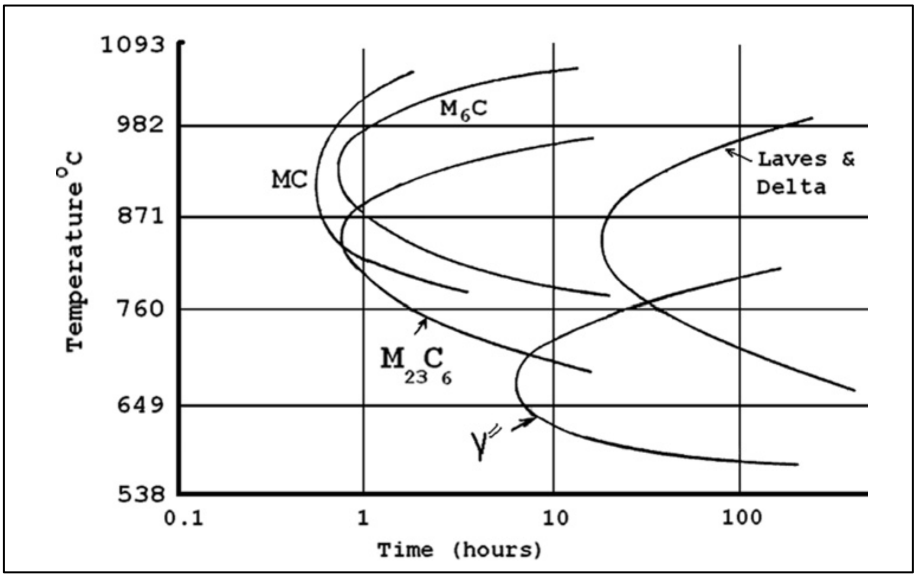


FIGURE 7: TIME-TEMPERATURE-TRANSFORMATION-DIAGRAM ALLOY 625 [16]

It is apparent from the TTT diagram that various types of carbides, such as MC ('M' is mainly Nb and Ti), $M_{23}C_6$, ('M' is mainly Cr) and M_6C ('M' is mainly Ni, Nb and Mo) are formed in this alloy. These precipitations1 depend upon various factors, including history of solidification, carbon concentration and head treatment temperature. Apart from the carbides and Laves phases, mostly formed during the solidification process, several other ordered phases, such as γ' (Ni_3 [Ti,Al]), γ'' (Ni_3Nb), δ (Ni_3[Nb,Mo]), Ni_2(Cr,Mo) also precipitate in Alloy 625. The TTT diagram however does not show the Ni_2 (Cr,Mo) phase that is formed after aging below 873 K and is known to dissolve if heated above this temperature. [16]

4.4.4 MACHINING AND WELDING BEHAVIOUR

Due to the high ductility and work hardening of the A625, machining is costly. For machining, a low cutting speed and a low feed rate should be selected; an adequate machining depth is important in order to undercut the work-hardened zone. [17]

Precipitation hardened nickel-base super alloys are susceptible to hot cracking in conventional welding processes, because of the formation of low melting eutectics. Furthermore, the creep resistance of these alloys decreases if the welding process leads to a reduction in grain size. The rapid temperature cycle and the concentrated heat input during EBW counteract here. Because A625 has no phase transformation in the solid state, there is only grain growth to be expected in the HAZ; starting from the melting zone, the grain size decreases continuously. Working with nickel requires a maximum of cleanliness; Sulphur (comprised in oil, grease, ...) can form the low melting Ni-Ni3-S2 eutectic (melting temperature 637°C). [17]

4.5 ARC WELDING / SMAW

In this thesis the shielded metal arc welding (SMAW) process was used for experimental investigation (see chapter 6).

At SMAW the electric arc is burning between a coated melting electrode and the work-piece. This welding circuit can be seen in Figure 8. Basically it consists of a welding machine, an electrode and ground cable, the electrode holder and an electrode.

The welding arc and the molten base material are protected from air by the shielding gas out of the coating and the slag. This process is shown in Figure 9.

This welding process is versatile useable at all welding positions and especially in the field. The machines for welding are relatively simple and cheap.

With this process different engineering materials can be welded. Theses are ferrous materials, nickel and nickel-alloys, copper and aluminum materials.

It is possible to weld thin metal sheets (1,5mm) with single layer technique, or thicker sheets (up to 50mm) with multi layer technique. [18]

Advantages

- Possibility of welding at construction site
- Welding devices not as expensive as for EBW
- No vacuum chamber needed

Disadvantages

- Long welding time for thicker metal sheets (e.g. multi layers)
- Welding joint preparation (different groove types)
- Atmospheric influences (e.g. Dust, humidity, Oxygen)
- Higher total heat input per unit length of weld (low welding speed)

4.5.1 EQUIPMENT

In Figure 8 the equipment for manual arc welding is shown. Basically it consists of a power source, ground and electrode cable and the electrode holder.

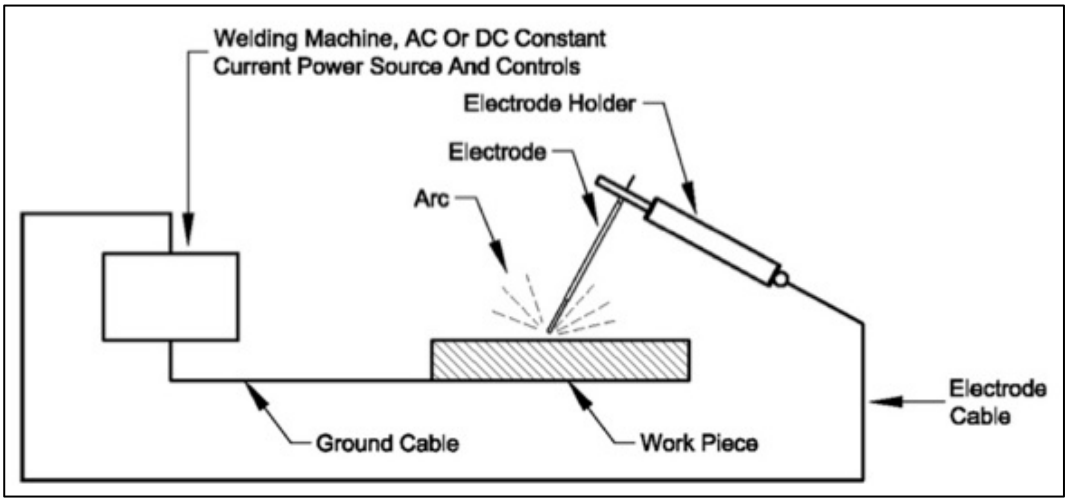


FIGURE 8: WELDING CIRCUIT FOR A SHIELDED METAL ARC WELDING (SMAW) [19]

Figure 9 shows the detailed welding process. It can be seen, how the electrode is melting and the weld pool is formed.

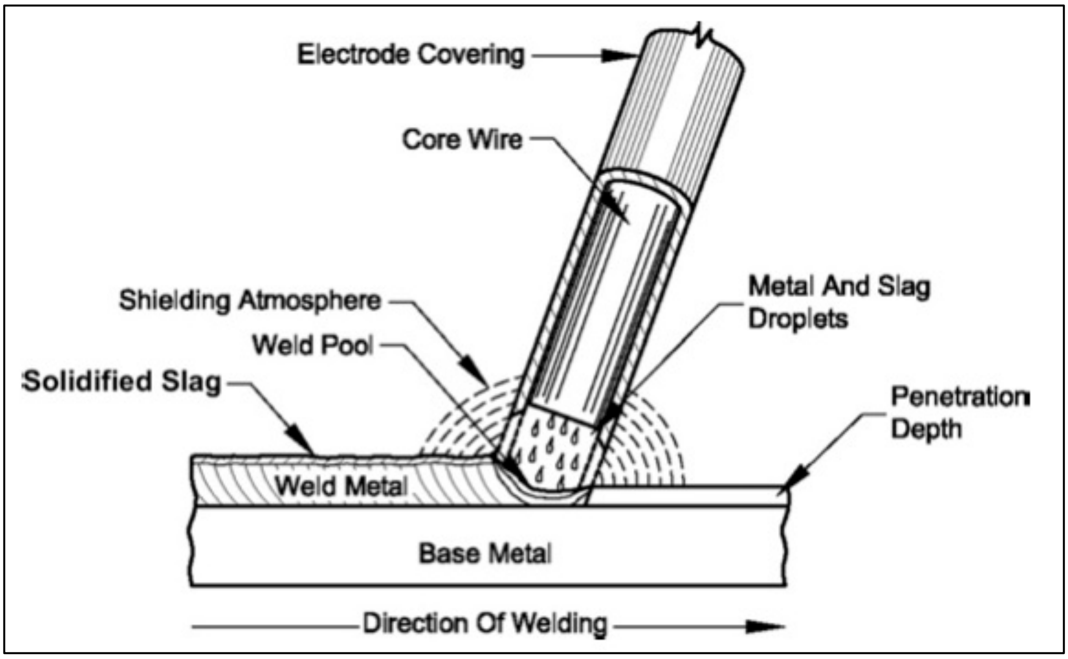


FIGURE 9: WELDING PROCESS FOR SMAW [19]

Filler Materials

Due to different welding processes the industry provides different types of filler materials for nickel-base alloys. The following chapter gives a short overview about the possibilities and differences.

4.5.2 FILLER METAL NIBAS 625

GMAW solid wires
GMAW flux cored wires
SMAW electrodes

For gas or shielded metal arc welding (GMAW / SMAW) of high-quality joints, filler metals of Nibas 625 for alloy 625, alloy 825 as well as Cr-Ni-Mo stainless alloys with high Mo-content are applied. Furthermore theses alloys are recommended for high-temperature materials (creep and heat resistant) and cryogenic materials as well as for joining of dissimilar steels and also for difficult to weld steels.

Nibas 625 filler materials can be used for pressure vessel fabrication for service temperatures range -196 °C to 550 °C as well as for high-temperature applications for scaling resistance limits up to 1200°C (S-free atmosphere). Due to the weld metal embrittlement between 600 - 850°C, this temperature range should be avoided. Highly resistant to hot cracking; furthermore, C-diffusion at high service temperatures or during post weld heat treatment of dissimilar steels is largely inhibited.

Further advantages of Nibas 625 filler materials are the extreme resistance to stress corrosion cracking and pitting, the thermal shock resistance of the fully austenitic microstructure, the low coefficient of thermal expansion (in between C-steels and austenitic Cr-Ni (Mo) steels). Wire and weld metal satisfy highest quality standards.

The electrodes have excellent welding characteristics in all positions except vertical-down, easy slag removal, high resistance to porosity. Electrodes and weld metal meet highest quality requirements. [20], [21]

FIGURE 10: FILLER MATERIAL NIBAS 625

Figure 10 shows the packaging of the filler material used for the experiments.

4.5.3 FILLER METAL NIBAS 617

GMAW solid wires
SMAW electrodes

These filler materials are suitable for joining high-temperature and similar nickel-base alloys, heat resistant austenitic and cast alloys, such as 2.4663 (NiCr21Co12Mo), 2.4851 (NiCr23Fe), 1.4876 (X10NiCrAlTi3220), 1.4859 (GX10NiCrNb3220). The weld metal is resistant to hot cracking and is used for service temperatures up to 1100°C due to its high scale and temperature resistance Furthermore this weld metal has high resistance to hot gases in oxidizing and carburized atmospheres, e.g. gas turbines, ethylene production plants.

The electrodes can be welded in all positions except vertical-down. It has a stable arc and easy slag removal. [20], [21]

4.6 ELECTRON BEAM WELDING (EBW)

For the generation of the electron beam a tungsten cathode is heated to enable a thermal emission of electrons out of the cathode surface. Between cathode and anode a high voltage (60-150kV) is applied. This voltage accelerates the electrons to 2/3 a speed of light and they impact towards the work piece, whereby they are focused via magnetic lens. Due to this focusing to a minimum beam diameter of 0,1 – 0,2mm a very high energy densities of > 10^6W/cm^2 is achieved. If the electrons impact on the work piece, they convert the kinetic energy into thermal energy. As a consequence the work piece is heated, partially melted or vaporized. During the conversion x-rays are formed and absorbed by a plumb lining of the vacuum chamber.

To avoid an oxidation of the cathode and an deflection of the beam (due to collision with gas particles), the whole process is performed in vacuum. The vacuum level is about 10^{-5}-10^{-6} mbar in the beam generator and about 10^{-4}-10^{-5} mbar in the working chamber. For the generation of this high vacuum, pumps (piston, diffusion and turbo pumps) are necessary. They have a high amount on the whole investment for EBW equipment. [18]

4.6.1 HISTORY

Electron beams apply the principles of electro-optics, which have been well defined and explored since the beginning of 1920s. The use of electron beams in welding was discovered a few decades later by Dr. Karl-Heinz Steigerwald and Dr. Jacques-André Stohr. They both worked independently on this topic. Steigerwald experimented with electron microscopes for the Allgemeine Elektrizitäts-Gesellschaft (AEG), a German producer of electrical equipment. He discovered the potential of electron microscopes for drilling and welding. Steigerwald found a solution and was looking for applications. Stohr who worked for the Commissariat à l' énergie atomique (CEA) and had to solve the problem of welding reactive materials. He discovered the use of electron beams in welding accidentally during manipulations on X-ray tubes. [22]

In Germany AEG considered this technique uninteresting. Fortunately the American patent broker, Mr. Irving Rossi, realized the potential of this technology and funded Steigerwalds research. In 1952 he built the first electron beam machine. Finally, in 1958, the first deep penetration welds in a zircaloy plate were performed. [23]

The availability of capital in nuclear- and aerospace industries in the early 1960's was of essential importance for the development of this technology. Just shortly after the pioneering work of Steigerwald, electron beam welding started to be used industrially.

- welding of synchronizing rings to gears; Volkswagen (1961)
- welding of artificial hip joints (1963)
- welding of water-cooled aluminum pistons for car engines (1969) [24]

4.6.2 EQUIPMENT

All EBW systems are constructed of the same basic modules, as shown in Figure 11: EBW machine layout.

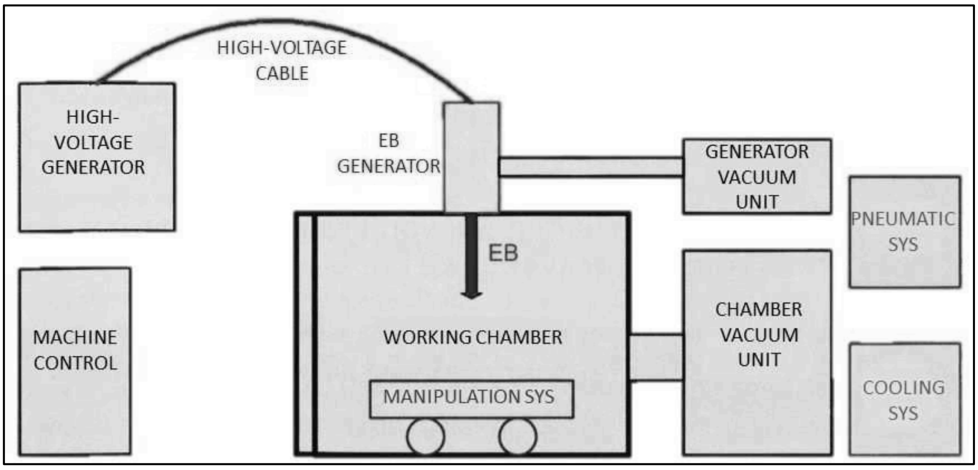


FIGURE 11: EBW MACHINE LAYOUT [25]

The High-voltage generator provides the electric power needed in the EB generator (or EB gun) to generate the electron beam. Moreover, the magnetic lenses for beam focusing, adjusting and deflecting are located inside the generator. The EB generator is separated from the working chamber by a valve. A constant high vacuum in the generator can be maintained, while venting the working chamber. The manipulation system (e.g. rotary table) can perform a macroscopic movement of the work piece. The generator vacuum unit and the chamber vacuum unit contain several different vacuum pumps to create the required vacuum (generator $p_{gen}≈10^{-5}$mbar; chamber $p_{cham}≈10^{-3}$mbar). The cooling system regulates the temperature of the power components. The pneumatic system is needed for valve controlling. The functions of the whole system can be controlled and monitored by the machine control. [26]

4.6.3 BEAM GENERATION

The beam generation takes place in the EB generator. Its main components are shown in Figure 12: EB generator .

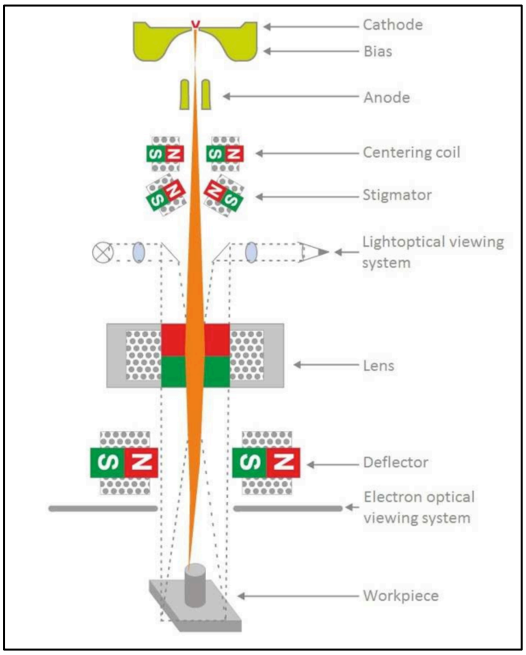


FIGURE 12: EB GENERATOR [27]

The cathode is the electron source. It is a flat ribbon filament usually made of tungsten. By heating up the cathode, electrons gain enough thermal energy to release the material surface. They gather around the filament and form an electron cloud. The number of the emitted electrons correlates with the temperature of the filament, as shown in Figure 13: Emission current density over cathode temperature. [22]

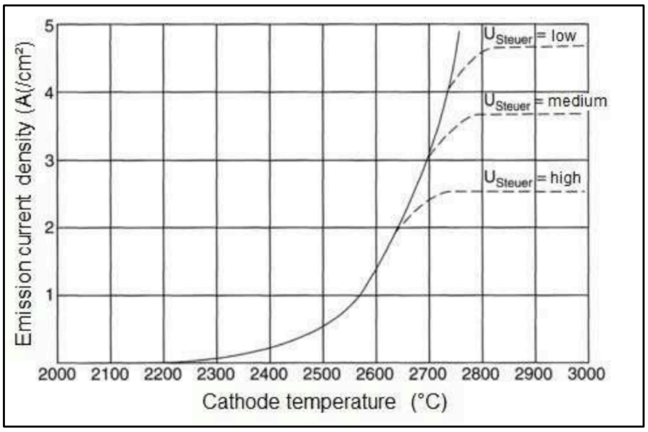


FIGURE 13: EMISSION CURRENT DENSITY OVER CATHODE TEMPERATURE [28]

The dashed lines represent the current density as a result of the auxiliary voltage of the bias. The bias (or Wehnelt-cylinder) is needed to control the beam current; a negative voltage in the bias reduces the beam current and the beam is pinched. By pinching the beam the bias also adjusts the location of the first real beam crossover. The position of the beam crossover is important for the divergence of the beam, which influences the focal position. Figure 14: Triode system shows schematically the build-up of this so called triode system. [22]

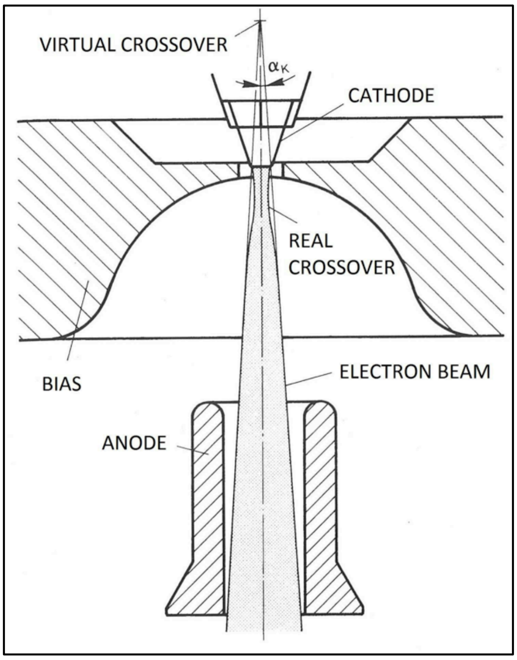


FIGURE 14: TRIODE SYSTEM [28]

The bottom part of the triode system is the anode, which is contrary to the cathode at ground potential. The electric field between these two components is responsible for the acceleration of the electrons. The acceleration voltage is constant during welding. The power of the beam is adjusted by the beam current, which is equivalent to the number of electrons in the beam per unit time. [22]

Behind the anode, a set of lenses is required to shape the electron beam and to position it accurately. This section in the EB gun is called beam optics. The magnetic lenses use the Lorentz force to manipulate the path of the electrons. The lenses consist of copper coil inside the iron pole pieces. The first lens is called centering coil (Figure 15: Centering coil). It is used to keep the electrons in the center of the gun to minimize lens errors. The stigmator (Figure 16: Stigmator) controls the beam shape by correcting the astigmatism. [22]

The then following focal lens, alters the focus of the beam, which is important to place the crossover in the right position related to the workpiece surface. Furthermore the focal lens is responsible for the divergence of the beam; thereby for the minimum beam diameter on the surface of the workpiece too, which is equal to beam intensity in this spot. [22]

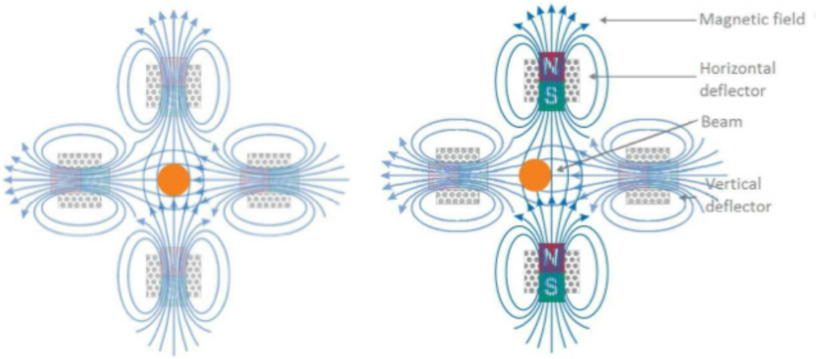


FIGURE 15: CENTERING COIL [27]

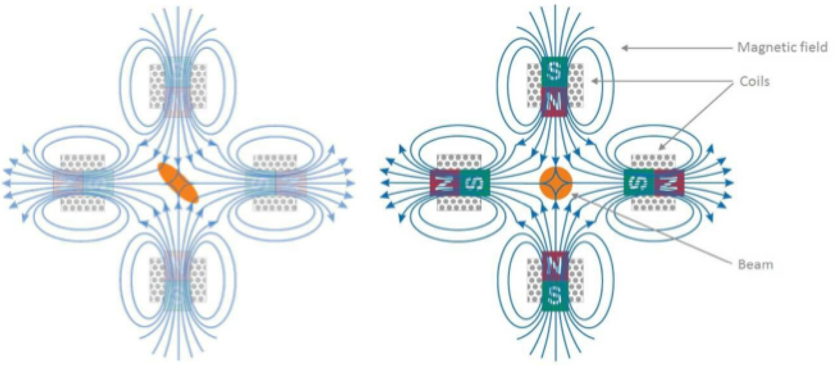


FIGURE 16: STIGMATOR [27]

The deflector is the bottom part of the EB generator. The working principle of this lens is equal to the centering coil. Beam deflection is performed direct to the beam across the work piece. Deflection can be done very rapidly because the beam has marginal inertia. Because of this, several special welding techniques can be applied (beam oscillation, simultaneous welding and beam wobbling).

In addition to the beam optics a light-optical viewing system and an electron-optical viewing system are installed. Both systems are made for controlling the welding process. The light-optical system is a charge-coupled device (CCD) camera. The electron-optical system uses the backscattered electrons and the secondary electrons to create an image; the same principle as used in a scanning electron microscope (SEM). [22]

4.6.4 ADVANTAGES

- Accurately controllable energy density and the small beam size makes it possible to control dilution and to weld with high precision and thus weld both very thin and very thick metals, i.e. from 0.025- 300 mm.
- Possible accurate beam alignment at any position allows the two base metals to melt selectively for a better setting of the metallurgical behavior.
- Low total heat input per unit length of weld produces narrow weld bead and HAZ, resulting in low residual stresses and minimum distortion, which can cause serious problems for conventional fusion welding processes.
- It is possible to solve problems associated with metallurgical incompatibility more accurately with EBW when using a suitable filler material, although this can also be a possible solution for arc welding, too.
- High purity environment (vacuum) for welding minimizes surface contaminations like oxygen, nitrogen and hydrogen, what is particularly beneficial for reactive and refractory alloys.
- Dissimilar-metal combination involving high thermal conductivity metals such as copper can be welded without preheating. [29]

4.6.5 DISADVANTAGES

- Expensive welding equipment
- Size of weldable work-piece depend on the vacuum chamber size

4.6.6 LIMITATIONS

- Problems related to melting and mixing of dissimilar metals during fusion welding still exist.
- Possible beam deflection by electrostatic and magnetic fields when welding dissimilar alloys.
- Vacuum environment normally necessary, i.e. welding alloys with a high vapor pressure is not possible
- High accuracy requirement in groove preparation.

- Rapid solidification may result in brittleness or high hardness of the weld and many welding defects, e.g. porosity.
- Use of vacuum chamber may reduce product size and limit the product design.
- Although beam oscillation can minimize the groove preparation requirement, it may cause problems for dissimilar-metal joining due to the possible uncontrollable fusion ratio of the two metals.
- High equipment and running cost. [29]

4.7 DISSIMILAR WELDING

Dissimilar-metal joints are characterized particularly by compositional gradients and microstructural changes, which yield large variations in chemical, physical, and mechanical properties across the joint. Therefore the joining of dissimilar alloys is normally far more complex than the joining of similar alloys. [29]

4.7.1 WELDING PROCEDURE SPECIFICATION (WPS)

According to ISO 15609-1:2004 (specification and qualification of welding procedures for metallic materials – Welding procedure specification – Part 1: Arc welding) [30]

A WPS is a document that describes how welding has to be carried out in production. They are recommended for all welding operations and many application codes and standards make them mandatory.

At first a preliminary Welding Procedure Specification (pWPS) has to be generated. If the welded specimen passes all the tests regarding to ISO 15614 the pWPS turns into a WPS. In Figure 17: pWPS DA_Grossegger the pWPS for the welding joint of that thesis can be seen.

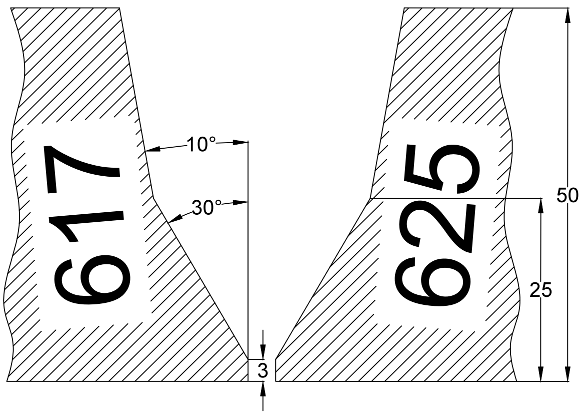
In this case two different materials had to be welded: Alloy 617 forged and alloy 625 cast material. The butt weld joint preparation was a double 'V'-shaped groove of 30° angle to the vertical at the root and 15° angle at the top. The root face was 3mm and the welding gap was about 2mm. The angle presetting was approximately about 3° to compensate the distortion due to weld metal shrinkage (see Figure 24, Chapter 5.3). Here two welding procedures are applied. The Tungsten Inert Gas Procedure (TIG 141) for the root runs and the Shielded Metal Arc Welding Procedure (SMAW 111) for the filler and the cover runs. After the root was weld, the backside was grinded out and a sealing run was performed. This was also done using the TIG process. The sealing run was examined by penetration testing (PT) to guarantee a crack free welding. As filler material the Nibas 625 instead the Nibas 617 was used, because of better experience on VAGT side. The interpass temperature had to be below 150°C to avoid the danger of hot cracking. The control of the welding machine regarding current and voltage was done by the welder's preferences inside the limits from the pWPS.

preliminary Welding Procedure Specification (pWPS)

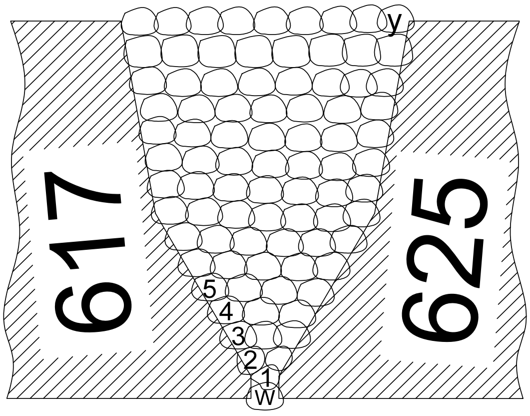
Client:	voest alpine Traisen	Project:	DA Großegger
Procedure Description:	50mm weld	Number:	pWPS_20131007-2
Material:	alloy 617 & alloy 625		
Position:	PA		
Preheat [°C]:	20°C		
	root	**filler**	**cover**
Welding Process:	TIG	SMAW	SMAW
Filler:	FOX Nibas 625-IG	FOX Nibas 625	FOX Nibas 625
Polarity:	=/-	=/+	=/+
Shielding Gas:	ceramic backing	-	-
Purge Gas:	100% Argon	-	-

Pass No.	Process	Filler size [mm]	Amps	Volts	Interpass Temp. [°C]	Current / Polarity	Heat input [kJ/cm]
1-3	141	2,4	180-190	12-18	<150	=/-	8,4
4	111	3,2	65-95	22-24	<150	=/+	3,7
5-14	111	4	90-120	24-26	<150	=/+	4,4
15-y	111	5	140-160	24-28	<150	=/+	6,5

Design of the joint



welding sequence



grind out root / weld a sealing run from the backside

International Welding Engineer Approved	Christof GROßEGGER / Michael MESSERER
Approved for Client	voestalpine

FIGURE 17: PWPS DA_GROSSEGGER (TRAISEN, MARCH 10, 2014)

4.7.2 WELDING PROCEDURE TESTING

According to ISO 15614-1:2004 (Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys). It is necessary to do a Welding Procedure testing to prove the qualification for performing this welding joint for customers. This Welding Procedure Testing has to be done according to the standards of ISO 15614.

4.7.3 WELDING PROCEDURE QUALIFICATION RECORD (WPQR)

The WPQR is a representation of the specimens testing results. The tester has to date, stamp and sign them. It is recommended to use a WPQR template for a consistent design of the results. Figure 18: Specimen Layout Pipe Weld for mechanical and metallographic testing [31] and Figure 19: Specimen Layout Butt Weld for mechanical and metallographic testing [31] shows the areas, where the test specimens are machined out from the welded part.

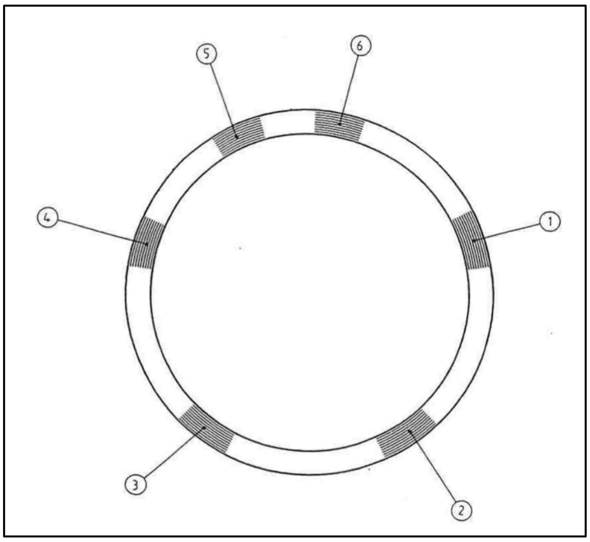


FIGURE 18: SPECIMEN LAYOUT PIPE WELD FOR MECHANICAL AND METALLOGRAPHIC TESTING [31]

Area 1	tensile test specimen, bending specimen, side-bending specimen
Area 2	notched specimen
Area 3	tensile test specimen, bending specimen, side-bending specimen
Area 4	metallographic specimen, hardness test specimen
Area 5	metallographic specimen
Area 6	metallographic specimen

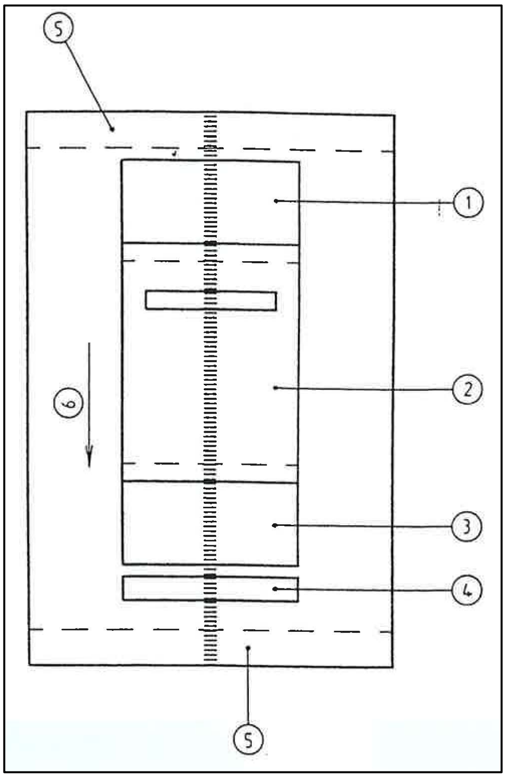


FIGURE 19: SPECIMEN LAYOUT BUTT WELD FOR MECHANICAL AND METALLOGRAPHIC TESTING [31]

Area 1	cross tensile test specimen, bending specimen, side-bending specimen
Area 2	notched specimen
Area 3	cross tensile test specimen, bending specimen, side-bending specimen
Area 4	metallographic specimen, hardness test specimen
Area 5	waster: if t>25mm, waster=50mm width
Area 6	welding direction

The specimen layout in Figure 19 was applied for the present investigation, see chapter 6.

5 METHODS

This chapter provides an overview about the materials used and the required tests for performing a welding procedure test.

Due to a lack of material it was not possible to perform all demanded tests according to ISO 15614-1 (Specification and qualification of welding procedures for metallic materials - Welding procedure test - Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys) [32] and 15614-11 (Specification and qualification of welding procedures for metallic materials- Welding procedure test- Part 11: Electron and Laser beam welding) [31]. So the side-bending test (see 5.5.3) was not performed.

5.1 WELDING EQUIPMENT

The welding machine used for TIG and SMAW welding was a Fronius MagicWave 3000. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows this welding machine. It is a fully digital controlled AC/DC power source, useable for both welding processes. It provides a maximum welding current of 300A and a highly stable arc due to its digital welding process control. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the characteristics of the power source. This is the reason for the stable arc. The vertical characteristic of current and voltage enables a nearly constant arc-power (P=U*I) in case of variations of the arc-length. This variation cannot be avoided, due to the manual handling. [18], [33]

FIGURE 20: FRONIUS MAGICWAVE 3000

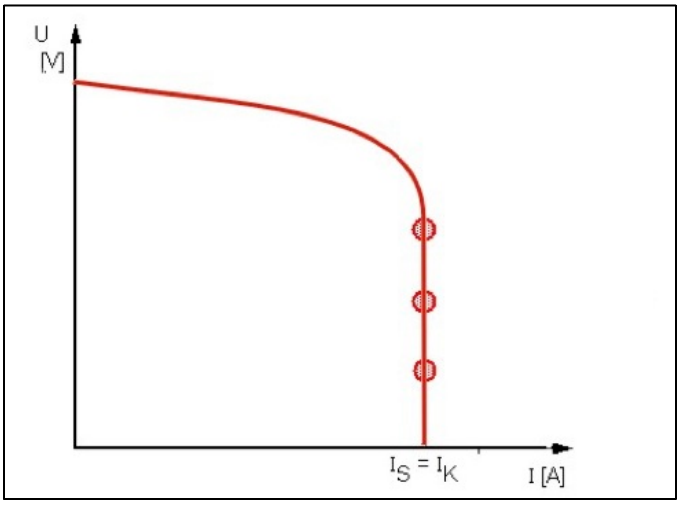


FIGURE 21: POWER SOURCE CHARACTERISTICS [18]

5.2 MATERIALS

The materials investigated in this thesis were provided by the voestalpine Gießerei Traisen (VAGT).
The materials were investigated at two different conditions: "As welded" (AW) and after a heat treatment, called "post welding heat treatment" (PWHT).

The heat treatment was done at VAGT as followed:

Heating rate:	50°C/h
Temperature:	800°C
Holding period:	4h
Cooling:	at air environment

5.2.1 CHARACTERISTICS ALLOY 617 – FORGED ALLOY

The labeling of the alloy 617 is NiCr22Co12Mo and the DIN standard materials number is 2.4663. The composition of the lot is listed in Table 3: Chemical composition of forged alloy A617 (in weight %) and the mechanical properties are shown in Table 4: Mechanical properties of forged alloy A617.

TABLE 3: CHEMICAL COMPOSITION OF FORGED ALLOY A617 (IN WEIGHT %) – (COMPANY ENPAR 73467/214158)

C	Si	Mn	P	S	Cr	Mo
0.065	0.04	0.02	0.002	0.002	21.99	8.72
Ni	**Co**	**Cu**	**Ti**	**Fe**	**Al**	**B**
55.31	11.61	0.02	0.41	0.59	1.14	0.001

TABLE 4: MECHANICAL PROPERTIES OF FORGED ALLOY A617 – (COMPANY ENPAR 73467/214158)

Rp 0.2% [N/mm^2]	Rm [N/mm^2]	A [%]	Z [%]	hardness [HB]
376	771	60	65	225

5.2.2 CHARACTERISTICS ALLOY 625 – CASTED ALLOY

The labeling of the alloy 625 is NiCr22Mo9Nb and the DIN standard materials number is 2.4856. The composition is listed in Table 5: Chemical composition of casted alloy A625 (in weight %) and the mechanical properties are shown in Table 6: Mechanical properties of casted alloy A625.

TABLE 5: CHEMICAL COMPOSITION OF CASTED ALLOY A625 (IN WEIGHT %) – (VAGT:505326-SP-NIBAS-625-SA-MEL)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	V	Ti
0.028	0.314	0.250	0.007	0.003	21.594	61.994	8.264	0.045	0.009	0.248
Al	**Mg**	**Nb**	**Co**	**Pb**	**B**	**Ta**	**Zr**	**N**	**Fe**	**W**
0.212	0.002	3.337	0.020	0.004	0.002	0.001	0.002	0.004	3.653	0.003

TABLE 6: MECHANICAL PROPERTIES OF CASTED ALLOY A625 – (VAGT:505326-SP-NIBAS-625-SA-MEL)

Rp 0.2% [N/mm^2]	Rm [N/mm^2]	A [%]	Z [%]	Ak1 [J]	Ak2 [J]	Ak3 [J]
265	549	52.7	46	300	278	316

5.2.3 CHARACTERISTICS WELD METAL 625 – ELECTRODES FOR SMAW

The type of the weld metal is produced by welding BÖHLER FOX NIBAS 625 stick electrodes for SMAW. The labeling according to ISO 14172 is E Ni 6625 (NiCr22Mo9Nb).

TABLE 7: CHEMICAL COMPOSITION OF THE MMA WELD METAL NIBAS 625 – (BÖHLER WELDING-GUIDE 2013)

C	Si	Mn	Mo	Cr
0.025	0.4	0.7	9	22
Nb	**Co**	**Ni**	**Fe**	**Al**
3.3	0.05	63.625	0.5	0.4

TABLE 8: MECHANICAL PROPERTIES OF THE MMA WELD METAL NIBAS 625 – (BÖHLER WELDING-GUIDE 2013)

Rp 0.2% [N/mm^2]	Rm [N/mm^2]	A [%]	Ak1 [J]
530	800	40	80

5.2.4 CHARACTERISTICS WELD METAL 625 – RODS FOR TIG

The type of the weld metal is produced by welding BÖHLER FOX NIBAS 625-IG rods for GTAW. The labeling according to ISO 18274 is S Ni 6625 (NiCr22Mo9Nb).

TABLE 9: CHEMICAL COMPOSITION OF THE TIG WELD METAL NIBAS 625-IG – (BÖHLER WELDING-GUIDE 2013)

C	**Si**	**Mn**	**Mo**	**Cr**
0.02	0.1	0.1	9.0	22
Nb	**Ti**	**Ni**	**Fe**	**-**
3.6	+	64.68	0.5	-

TABLE 10: MECHANICAL PROPERTIES OF THE MMA WELD METAL NIBAS 625 – (BÖHLER WELDING-GUIDE 2013)

Rp 0.2% [N/mm^2]	**Rm** [N/mm^2]	**A** [%]	**Ak1** [J]
540	800	38	160

5.3 Welding of test piece and joint preparation at VAGT

In Figure 22: Design of Welding Joint the cross section of the prepared joint can be seen. The reason for this design is that in comparison to a normal chamfer (U- or V-joint), less weld material is needed for the joint, because of the smaller angle of 10° from the middle to the top.

The welding was done by a certificated welder of VAGT according to the pWPS (see 4.7.1, Figure 17: pWPS DA_Grossegger). In Figure 23: Welding Sequence, the runs and passes according to the pWPS can be seen.

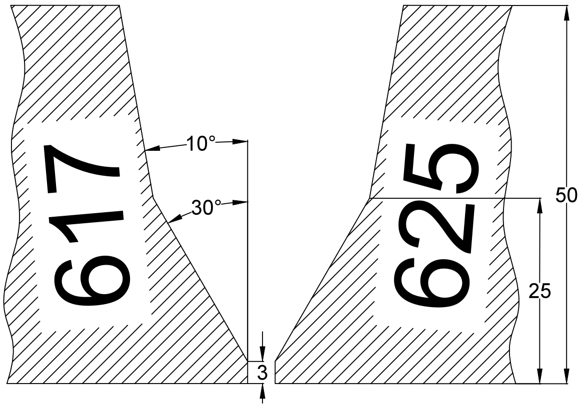


FIGURE 22: DESIGN OF WELDING JOINT

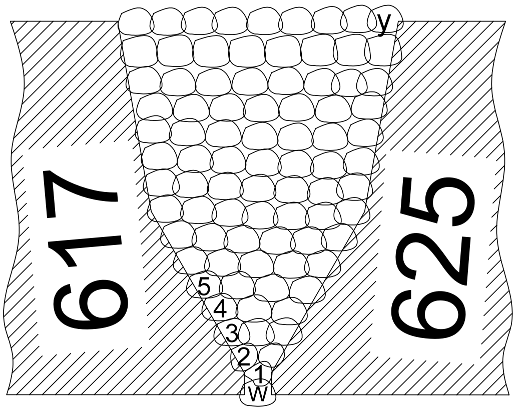


FIGURE 23: WELDING SEQUENCE TIG/SMAW

In Figure 24: Test-piece layout the real test-piece can be seen. It is the state just before the welding. To compensate the angular shrinkage due to welding, the test pieces do have an angle presetting of approximately 3-5° (dependent on the welders experience). After some welded layers the welding specimen became even. See Figure 25: Even Test-piece after TIG-welding of the root layers.

In Figure 26: Test-piece TIG Welding at VAGT, the welding process of the certified welder at work can be seen.

FIGURE 24: TEST-PIECE LAYOUT TACK WELDED (ANGLE PRESETTING 3-5° AND CERAMIC BACKING)

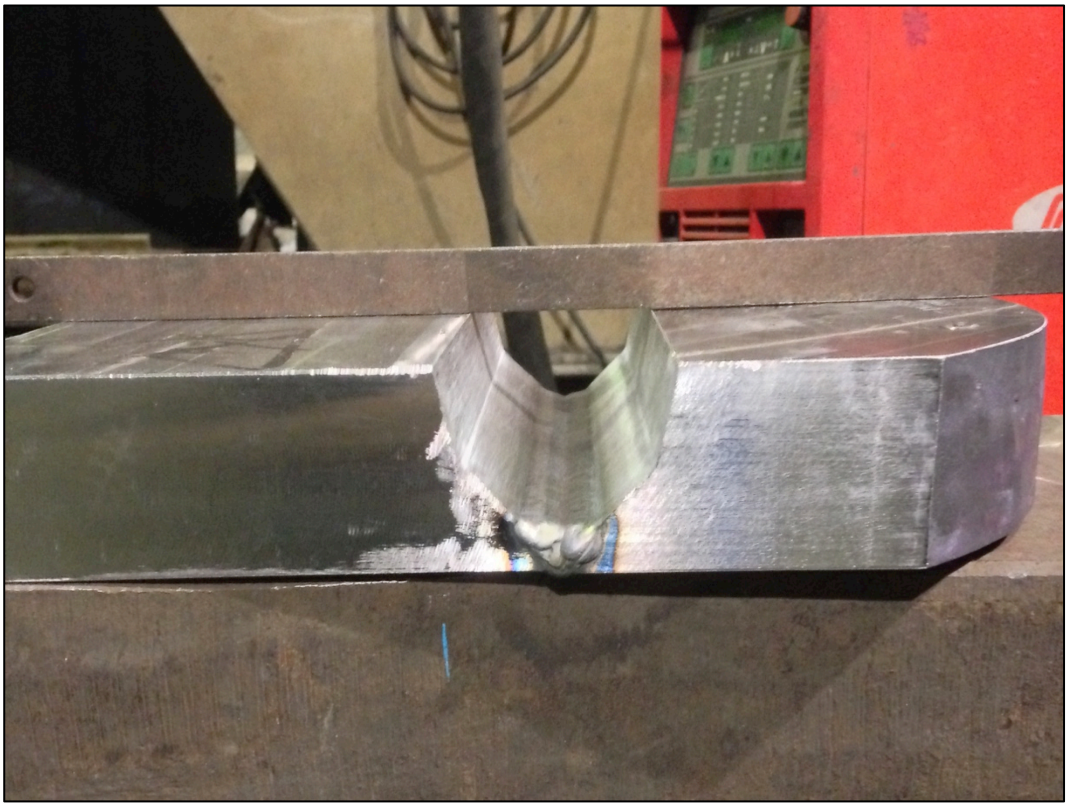


FIGURE 25: EVEN TEST-PIECE AFTER TIG-WELDING OF THE ROOT LAYERS

FIGURE 26: TEST-PIECE TIG WELDING AT VAGT

5.4 WELDING PROCEDURE TESTING

The performed welding procedure testing according to EN ISO 15614-1 is necessary for the qualification of a welding method for metallic materials. Within this test a test piece is welded in strict accordance to the preliminary welding procedure specification (pWPS). In case of a positive result of following destructive and non-destructive tests, a report about the qualification of the welding procedure is created (WPQR). Thereby the pWPS turns into a WPS and as a consequence to homologation for production.

The destructive and non-destructive tests according to the standard for a butt joint are listed in Table 11: non-destructive tests according to EN 15614-1 and Table 12: destructive test according to EN 15614-1.

TABLE 11: NON-DESTRUCTIVE TESTS ACCORDING TO EN 15614-1

Test-method	Test-range
Visual testing (VT)	100%
Radiographic (RT) or ultrasonic testing (UT)	100%
Penetration testing (PT)	100%

TABLE 12: DESTRUCTIVE TEST ACCORDING TO EN 15614-1

Test-method	Test-range
Tensile test	2 samples
Side bending test	4 samples
Notched-bar impact test	2 sets
Hardness test	Necessary
Macroscopy	1 sample

Remark: Due to a lack of material it was not possible to perform all tests according to the standard. Furthermore the welded test piece does not fulfill the minimum dimensions according to the standard (Figure 27: Dimensions Test sample). Figure 28: Dimensions Test sample DA_Grossegger shows the test piece, which was used for the welding procedure qualification tests.

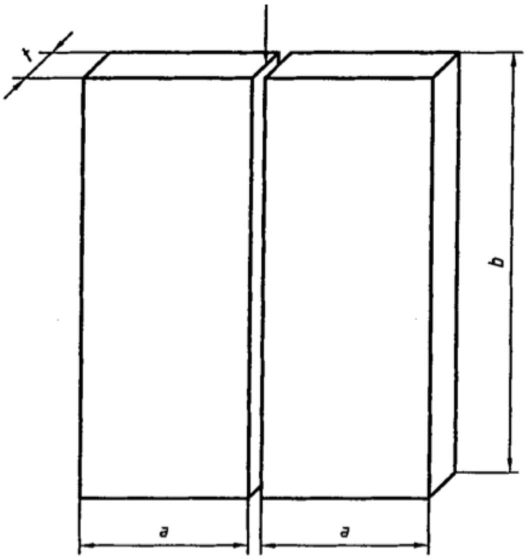


FIGURE 27: DIMENSIONS TEST SAMPLE ACCORDING TO EN 15614-1 [32]

The dimension of the test sample according to the standard, should be at least:

a: min. 150mm b: min. 350mm t: depth (50mm)

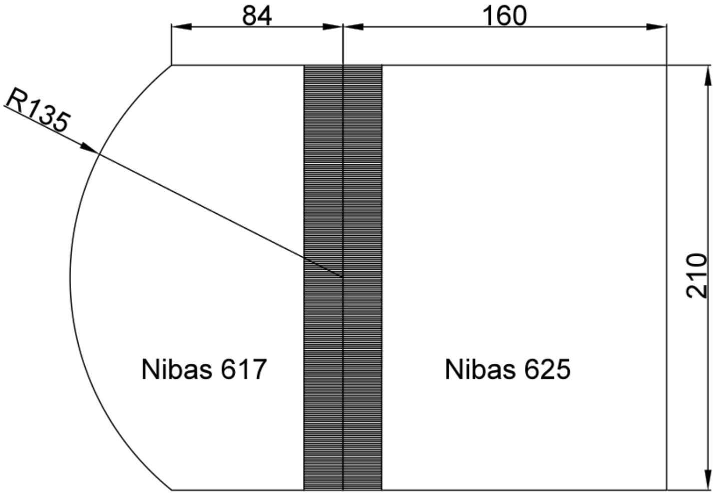


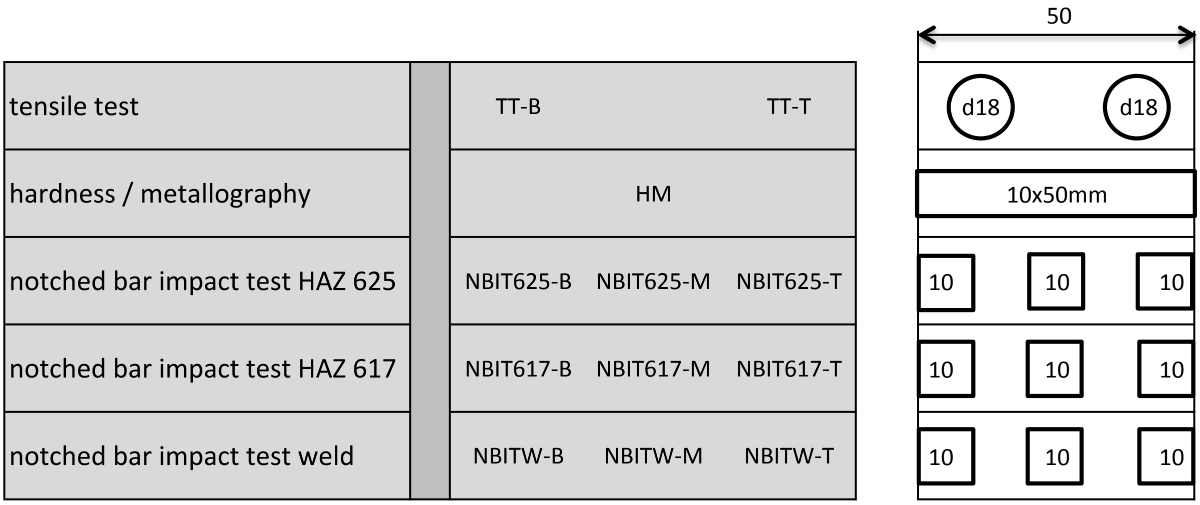
FIGURE 28: DIMENSIONS TEST SAMPLE DA_GROSSEGGER

The actual dimensions of the test sample are shown in Figure 28:

a: 84mm b: 210mm t: depth (50mm)

5.5 TEST LAYOUT

According to the standard ISO 15614-1 [32] and ISO 15614-11 [31] the following test specimen layout was chosen:



tensile test	TT-B		TT-T
hardness / metallography		HM	
notched bar impact test HAZ 625	NBIT625-B	NBIT625-M	NBIT625-T
notched bar impact test HAZ 617	NBIT617-B	NBIT617-M	NBIT617-T
notched bar impact test weld	NBITW-B	NBITW-M	NBITW-T

FIGURE 29: SPECIMEN LAYOUT EBW WELD

Abbreviations:

TT-B: tensile test – bottom
TT-T: tensile test - top
HM: hardness / metallography
NBIT: notched bar impact test
-B: bottom 617: alloy 617
-M: middle 625: alloy 625
-T: top W: weld

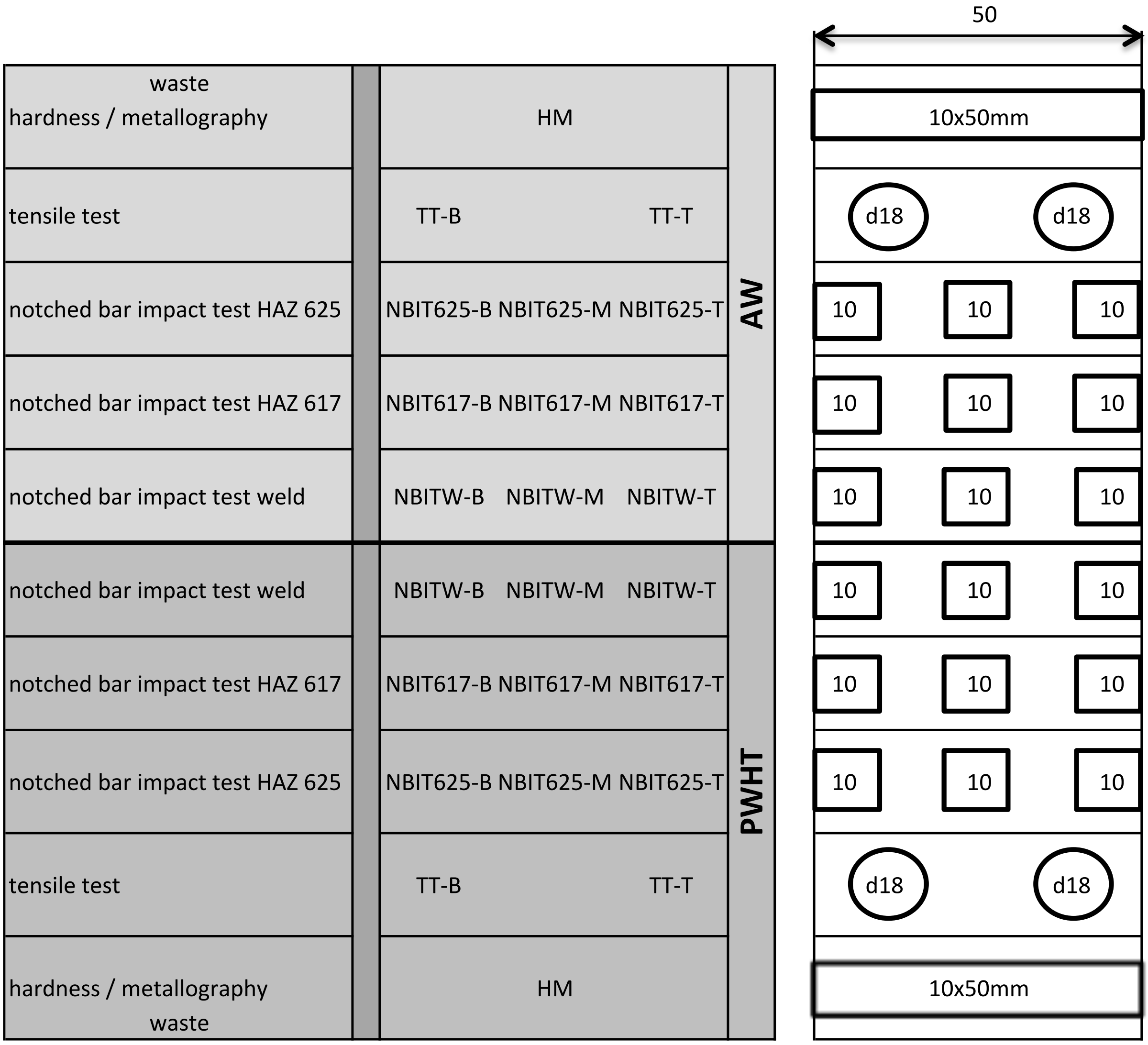


FIGURE 30: SPECIMEN LAYOUT TIG/SMAW WELD

Abbreviations:

TT-B:	tensile test – bottom		
TT-T:	tensile test - top		
HM:	hardness / metallography		
NBIT:	notched bar impact test		
-B:	bottom	617:	alloy 617
-M:	middle	625:	alloy 625
-T:	top	W:	weld
AW:	as welded		
PWHT:	post weld heat treatment		

5.5.1 Tensile Test

In DIN 50125 [34] the machining of the test specimen is defined. It is distinguished between A, B, C, D, E, F, G types of specimen. Figure 31: Specimen Tensile Test Type A [34] shows the layout of a tensile test specimen type A according to the standard.

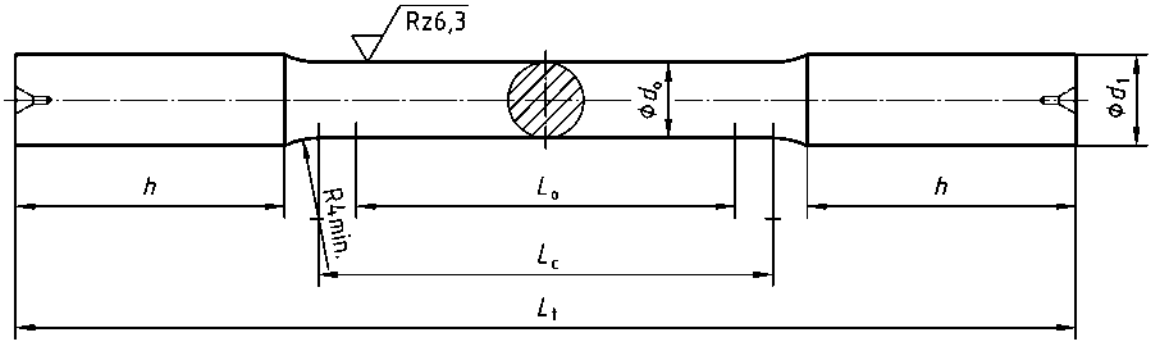


FIGURE 31: SPECIMEN TENSILE TEST TYPE A [34]

d_0	specimen diameter	12mm
d_1	head diameter	18mm
h	head height	55mm
L_0	starting length	60mm
L_c	test length	72mm
L_t	overall length	200mm

5.5.2 Notched-bar impact-bending Test (Charpy-V Test)

According to ÖNORM EN 10045-1 [35] specimens are distinguished between Charpy-V and the Charpy-U type. The test specimen geometry is machined as shown in Figure 32: Specimen Charpy-V Test – positions of the notch [11]. The Charpy-V tests were performed for the weld metal (a) and for the heat affected zone (b).

For this test a specimen notched in the middle, which is inserted between two supports and is broken through by a pendulum hammer. The impact energy absorbed (in Joule) is a measure for the materials toughness against instable crack propagation. As shown in Figure 33: Test Layout Notched-Bar Impact Test [4].

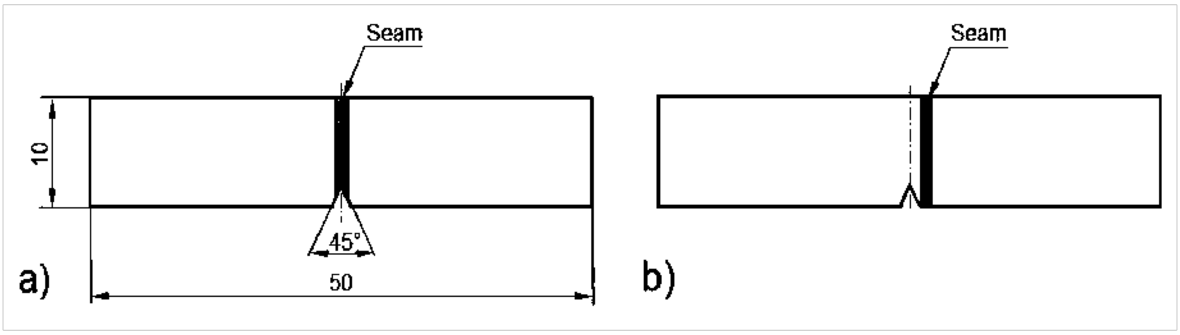


FIGURE 32: SPECIMEN CHARPY-V TEST – POSITIONS OF THE NOTCH [11]

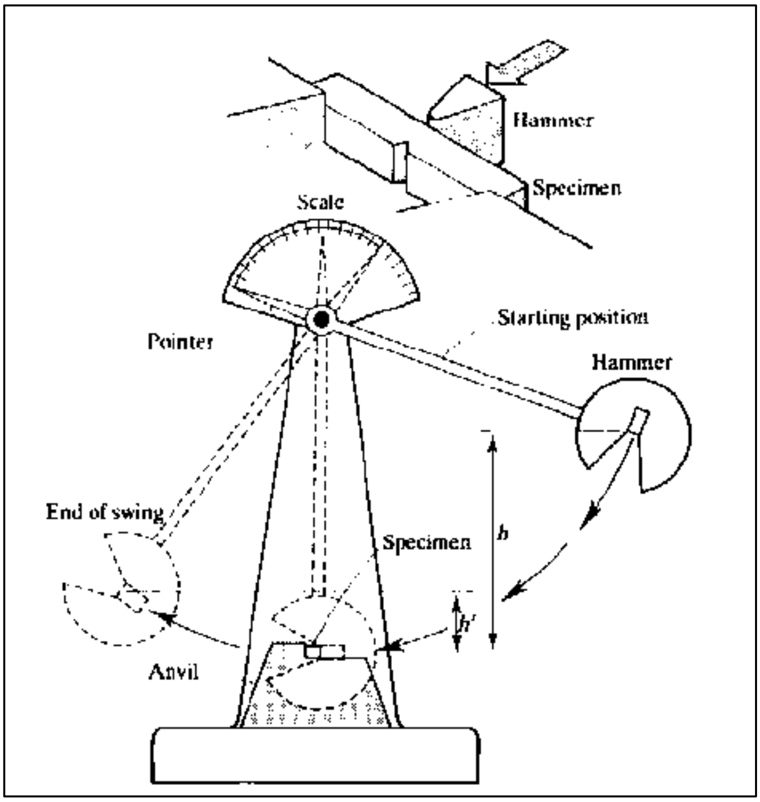


FIGURE 33: TEST LAYOUT NOTCHED-BAR IMPACT TEST [4]

5.5.3 SIDE BENDING TEST

According to DIN EN 910 [36] the side bend test is used for testing the deformability of butt welded joints. The specimen is mounted on rollers (diameter of 50mm) and is bended via a bending bolt. The deformation value is the bending angle at which the first crack can be identified.

Beside the bending angle the strain of the outside fiber can be determined. The welding joint design has a major influence on the achievable bending angle. Therefor defects like pores, slag inclusions, lack of fusions and cracks, are responsible in the case, that the claimed bending angle is not accomplished.

The bending angle is dependent on following factors:

- Quality of the specimen, specimen geometry, surface condition, ratio between tensile strength of weld deposit and base material (under-, even- or over-matched).
- Test assembly and execution, position of the root, support width, bending bolt diameter and deformation speed. [18]

The testing layout is shown in Figure 34: Side Bend Test Layout.

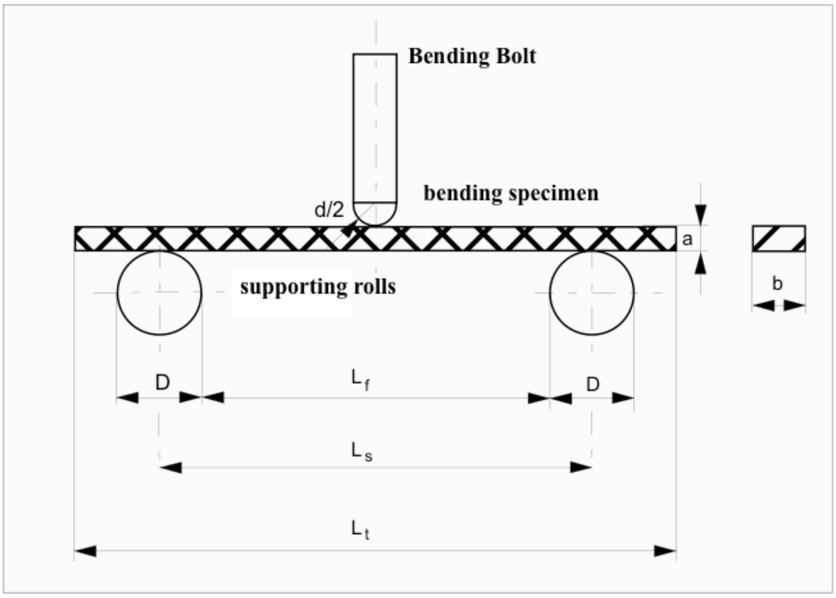


FIGURE 34: SIDE BEND TEST LAYOUT

The test specimen geometry is machined as shown in Figure 35: Specimen Side Bend Test [11].

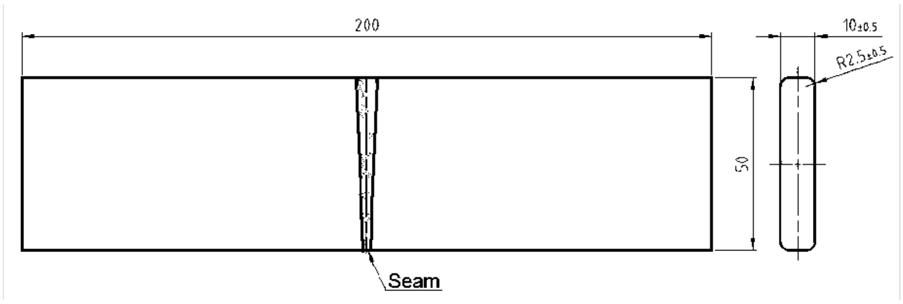


FIGURE 35: SPECIMEN SIDE BEND TEST [11]

5.5.4 HARDNESS TEST / HARDNESS LINE

According to ISO 15614-1 [32] and ISO 15614-11 [31] a hardness test for every weld is required. In general hardness tests at welded joints are performed after Vickers (DIN EN ISO 6507) with load forces of 49N or 98N (HV5 or HV10). The choice of the hardness load is mainly dependent on the material type. For hardness tests of welded joints the determinations according to DIN EN 1043 are mandatory. The tests can be executed as in-line or single imprints.[18]

The hardness test has to be done according to EN 1043-1 [37]. The applied test method was Vickers with a test mass of 10kg (HV 10). The hardness tests have to consist of three individual imprints in the weld zone, in the heat-affected zone and in both base materials. For specimen thicknesses over 5mm, two hardness lines have to be performed, at a position of 2mm below the top- and bottom-layer of the surface. In addition to the HAZ there should be hardness imprints as close as possible to the fusion line.

Figure 36: Hardness test layout and Figure 37: Hardness test layout EBW shows the layout of the hardness lines.

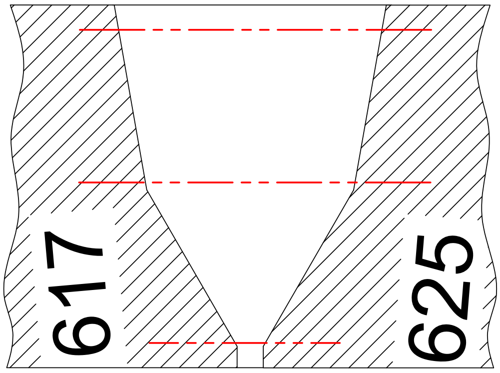


FIGURE 36: HARDNESS TEST LAYOUT TIG/SMAW

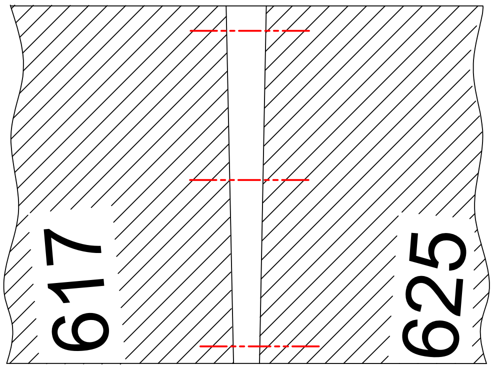


FIGURE 37: HARDNESS TEST LAYOUT EBW

5.5.5 MACROSCOPY AND ETCHING

According to OENORM EN 1321 [38] for macroscopy the specimen was machined in the way that the whole weld is visible in one picture. Subsequently the specimen was grinded manually using sandpaper with a grain size of 320, 500, 800, 1200, 2400 and 4000 per inch and finally polished using diamante dispersion. Considering the dissimilar weld and the generally bad etching behavior of alloy 617 and 625, the best etchant out of history (V2A) was used. The composition of the etchant is shown in Table 13: Etchant composition.

TABLE 13: ETCHANT COMPOSITION AND ETCHING PROCEDURE

Name	Composition	Etching-procedure	Characteristic
V2A	100ml water 100ml muriatic-acid 10ml nitric acid 2ml pickling-inhibitor	temperature: 50-70°C Macro: wipe Micro: immerse for some minutes	Macro: weld layer structure Micro: grain boundaries

5.5.6 MICROSCOPY

Normally microscopy is done with small specimen polished, etched and embedded in artificial resin. The maximum outer diameter of these specimens is 50mm.

According to OENORM EN 1321 [38] the specimen for macroscopy has to be stored after investigation, it is not allowed to cut these into smaller specimen suitable for microscopy. Therefor the whole macroscopy specimen was used for microscopy. This is not the best way for doing microscopy, because of the bad manipulation, but the only way possible. Figure 38 shows the used specimen for the investigations.

FIGURE 38: MACROSCOPY AND MICROSCOPY SPECIMEN TIG/SMAW

5.6 MATCALC CALCULATIONS

The aim of this chapter was just to get a feeling, which different phases can be formed after solidification (under thermodynamic equilibrium conditions) for the materials used.

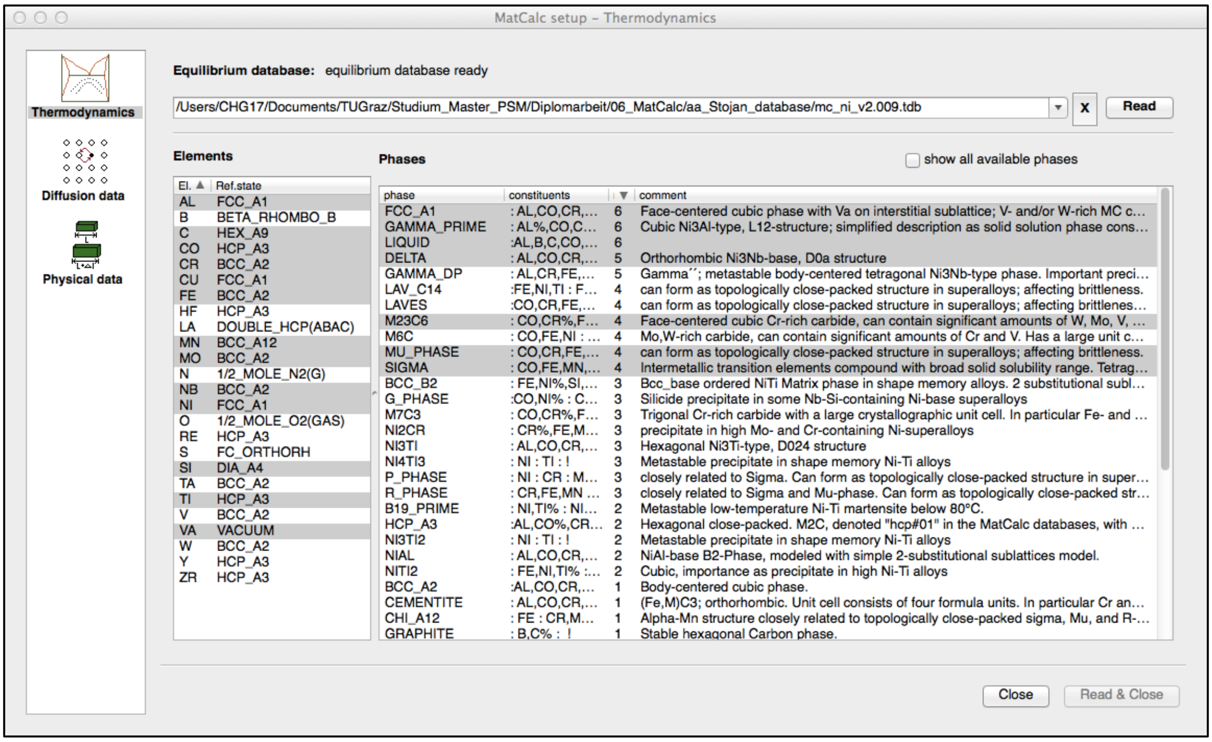
The thermodynamic equilibrium calculation was done using the software MatCalc 5.52. For the calculations the database "mc_ni_v2.009.tdb" was used.

What is MatCalc? - MatCalc is an ongoing project, which was initiated in 1993, with a PhD thesis of Ernst Kozeschnik [39] addressing the simulation of precipitation kinetics in steel. Over the years it has developed to a software project for computer simulation of phase transformations in metallic systems. The topics covered by the software MatCalc project include:

- Constrained and unconstrained phase equilibriums
- Precipitation kinetics
- Long-range diffusion
- Simultaneous diffusion and precipitation
- Phase transformations / moving phase boundaries
- Lattice Metropolis and kinetic Monte Carlo

The thermodynamic foundation of MatCalc is the CALPHAD method and (uncoded) CALPHAD-type databases. The kinetic modules of MatCalc are developed within the framework of solid-state phase transformations, with particular focus on computational efficiency and applicability to multi-component systems. [40]

Figure 39: MatCalc element selection shows the interface for selection of material elements and possible phases. The elements, which are contained in the material, have to be chosen, as well as the phases, which can appear. Subsequently the materials element composition as shown in Figure 40: MatCalc nominal material composition, has to be defined. After that the equilibrium calculations can be performed.



Equilibrium database: equilibrium database ready

/Users/CHG17/Documents/TUGraz/Studium_Master_PSM/Diplomarbeit/06_MatCalc/aa_Stojan_database/mc_ni_v2.009.tdb

Elements

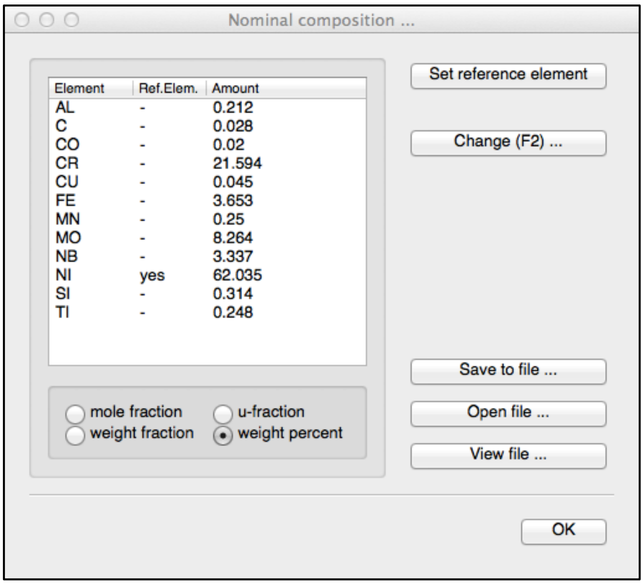
El. ▲	Ref.state
AL	FCC_A1
B	BETA_RHOMBO_B
C	HEX_A9
CO	HCP_A3
CR	BCC_A2
CU	FCC_A1
FE	BCC_A2
HF	HCP_A3
LA	DOUBLE_HCP(ABAC)
MN	BCC_A12
MO	BCC_A2
N	1/2_MOLE_N2(G)
NB	BCC_A2
NI	FCC_A1
O	1/2_MOLE_O2(GAS)
RE	HCP_A3
S	FC_ORTHORH
SI	DIA_A4
TA	BCC_A2
TI	HCP_A3
V	BCC_A2
VA	VACUUM
W	BCC_A2
Y	HCP_A3
ZR	HCP_A3

Phases

☐ show all available phases

phase	constituents	▼	comment
FCC_A1	: AL,CO,CR,...	6	Face-centered cubic phase with Va on interstitial sublattice; V- and/or W-rich MC c...
GAMMA_PRIME	: AL%,CO,C...	6	Cubic Ni3Al-type, L12-structure; simplified description as solid solution phase cons...
LIQUID	:AL,B,C,CO,...	6	
DELTA	: AL,CO,CR,...	5	Orthorhombic Ni3Nb-base, D0a structure
GAMMA_DP	: AL,CR,FE,...	5	Gamma´´; metastable body-centered tetragonal Ni3Nb-type phase. Important preci...
LAV_C14	:FE,NI,TI : F...	4	can form as topologically close-packed structure in superalloys; affecting brittleness.
LAVES	:CO,CR,FE,...	4	can form as topologically close-packed structure in superalloys; affecting brittlenes...
M23C6	: CO,CR%,F...	4	Face-centered cubic Cr-rich carbide, can contain significant amounts of W, Mo, V, ...
M6C	: CO,FE,NI : ...	4	Mo,W-rich carbide, can contain significant amounts of Cr and V. Has a large unit c...
MU_PHASE	: CO,CR,FE,...	4	can form as topologically close-packed structure in superalloys; affecting brittleness.
SIGMA	: CO,FE,MN,...	4	Intermetallic transition elements compound with broad solid solubility range. Tetrag...
BCC_B2	: FE,NI%,SI,...	3	Bcc_base ordered NiTi Matrix phase in shape memory alloys. 2 substitutional subl...
G_PHASE	:CO,NI% : C...	3	Silicide precipitate in some Nb-Si-containing Ni-base superalloys
M7C3	: CO,CR%,F...	3	Trigonal Cr-rich carbide with a large crystallographic unit cell. In particular Fe- and ...
NI2CR	: CR%,FE,M...	3	precipitate in high Mo- and Cr-containing Ni-superalloys
NI3TI	: AL,CO,CR,...	3	Hexagonal Ni3Ti-type, D024 structure
NI4TI3	: NI : TI : !	3	Metastable precipitate in shape memory Ni-Ti alloys
P_PHASE	: NI : CR : M...	3	closely related to Sigma. Can form as topologically close-packed structure in super...
R_PHASE	: CR,FE,MN ...	3	closely related to Sigma and Mu-phase. Can form as topologically close-packed str...
B19_PRIME	: NI,TI% : NI...	2	Metastable low-temperature Ni-Ti martensite below 80°C.
HCP_A3	:AL,CO%,CR...	2	Hexagonal close-packed. M2C, denoted "hcp#01" in the MatCalc databases, with ...
NI3TI2	: NI : TI : !	2	Metastable precipitate in shape memory Ni-Ti alloys
NIAL	: AL,CO,CR,...	2	NiAl-base B2-Phase, modeled with simple 2-substitutional sublattices model.
NITI2	: FE,NI,TI% :...	2	Cubic, importance as precipitate in high Ni-Ti alloys
BCC_A2	:AL,CO,CR,...	1	Body-centered cubic phase.
CEMENTITE	: AL,CO,CR,...	1	(Fe,M)C3; orthorhombic. Unit cell consists of four formula units. In particular Cr an...
CHI_A12	: FE : CR,M...	1	Alpha-Mn structure closely related to topologically close-packed sigma, Mu, and R-...
GRAPHITE	: B,C% : !	1	Stable hexagonal Carbon phase.

FIGURE 39: MATCALC ELEMENT SELECTION AND POSSIBLE PHASES (SCREENSHOT)



Element	Ref.Elem.	Amount
AL	-	0.212
C	-	0.028
CO	-	0.02
CR	-	21.594
CU	-	0.045
FE	-	3.653
MN	-	0.25
MO	-	8.264
NB	-	3.337
NI	yes	62.035
SI	-	0.314
TI	-	0.248

○ mole fraction ○ u-fraction
○ weight fraction ● weight percent

FIGURE 40: MATCALC NOMINAL MATERIAL COMPOSITION OF ALLOY 625 (SCREENSHOT)

5.6.1 EQUILIBRIUM CALCULATION ALLOY 617

Figure 41: Phase fraction plot alloy 617 shows the equilibrium calculation for the alloy 617. It can be seen which phases can appear at a dedicated temperature under the circumstance of infinitely time.

The main phase fraction down to approximately 300°C is the Gamma (FCC_A1), followed by the µ-Phase (MU) consisting mainly of Cr and Mo and ɣ' (Gamma-Prime), which appear at 900°C. Common precipitates are M23C6 carbides, which consists mainly of Cr-rich carbides and are stable up to 1279°C. The Ni2Cr carbides consist of Cr and Mo. The G-Phase consists of Cr and Ti. Other phases, which are only thermodynamic stable at temperatures below 200°C are not that important. Solidus temperature is 1279°C, liquids temperature is 1351°C.

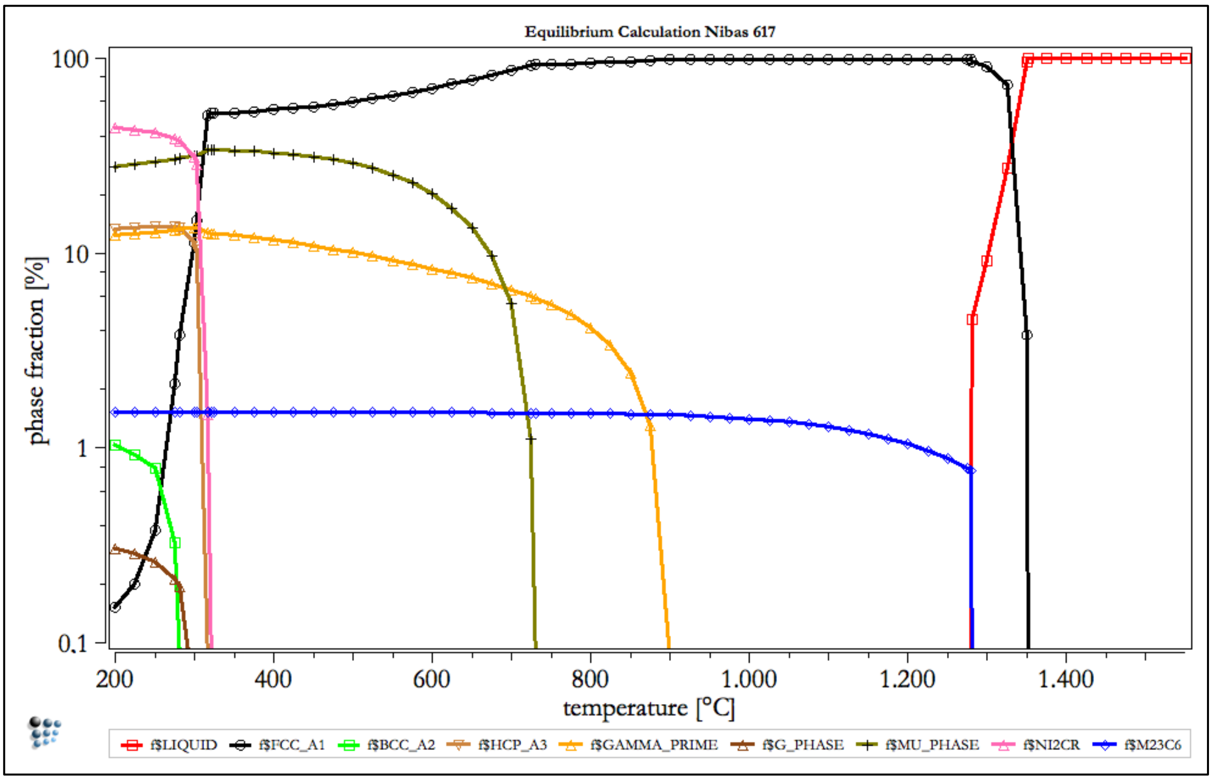


FIGURE 41: PHASE FRACTION PLOT ALLOY 617

The final equilibrium phase fractions of alloy 617 at 200°C are calculated by MatCalc as Table 14 shows.

TABLE 14: EQUILIBRIUM COMPOSITION MATCALC ALLOY 617 (AT 200°C)

Phases	Phase fraction [%]
MU	26
HCP_A3	13
Gamma_prime	12
M23C6	1,5
BCC_A2	1
G_phase	0,3
Matrix	rest

Table 15 shows the calculated phase transition temperatures by MatCalc for alloy 617.

TABLE 15: EQUILIBRIUM PHASE TRANSITION TEMPERATURES ALLOY 617

Phase transition	Temperature [°C]
Solidus	1279
Liquids	1351

5.6.2 EQUILIBRIUM CALCULATION ALLOY 625

Figure 42: Phase fraction Plot alloy 625 shows the equilibrium calculation for the alloy 625. It can be seen which phases can appear at a dedicated temperature under the circumstance of infinitely time. [41]

The most phase fraction for a temperature 200°C is the Gamma-phase (FCC_A1) , followed by the MU-Phase (appears at 870°C) and Delta-Phase (appears at 940°C). The fourth one is Gamma-Prime, which is only thermodynamic stable up to 700°C. The Sigma-Phase is only stable in a very small range around 900°C and below 250°C. M23C6 carbides consists mainly of Cr-rich and a little bit of Mo-rich carbides and begin to precipitate below 1200°C. Solidus temperature is 1271°C, liquids temperature is 1352°C.

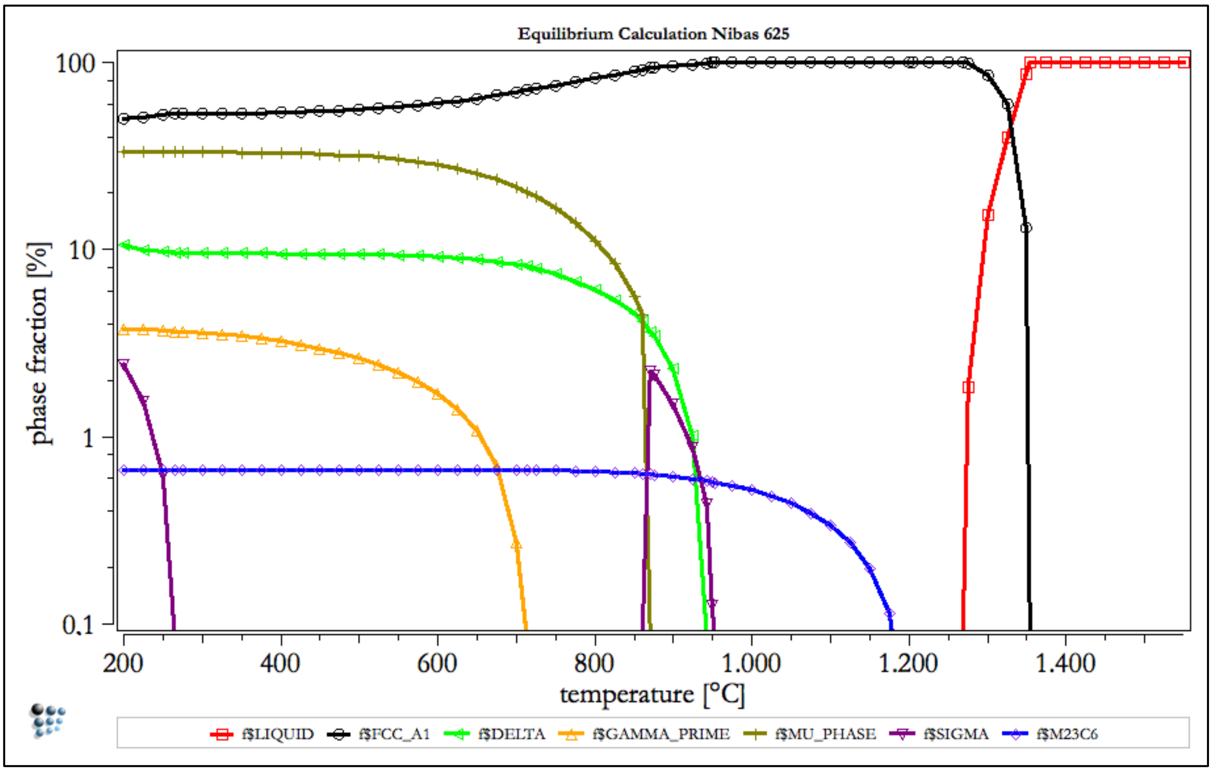


FIGURE 42: PHASE FRACTION PLOT ALLOY 625

The final equilibrium phase fraction of alloy 625 at 200°C are calculated by MatCalc as Table 16 shows.

TABLE 16: EQUILIBRIUM COMPOSITION MATCALC ALLOY 625 (AT 200°C)

Phases	Phase fraction [%]
MU	33
Delta	10
Gamma_prime	3,7
Sigma	2,4
M23C6	0,6
Matrix	rest

Table 17 shows the calculated phase transition temperatures by MatCalc for alloy 625.

TABLE 17: EQUILIBRIUM PHASE TRANSITION TEMPERATURES ALLOY 625

Phase transition	Temperature [°C]
Solidus	1271
Liquids	1352

5.6.3 EQUILIBRIUM CALCULATION WELD METAL ALLOY 625

Figure 43: Phase fraction plot weld metal 625 shows the equilibrium calculation for the weld metal material 625. It can be seen which phases can appear at a dedicated temperature under the circumstance of infinitely time. [41]

The phase with most phase fraction at 500°C is the Gamma-Phase (FCC_A1), followed by MU-Phase (appears at 930°C) and Delta-Phase (appears below 918°C). M23C6 carbides are formed below a temperature of 1200°C. They are not stable any more between 900°C and 950°C in favor of M6C carbides, which are formed in this temperature range. Both, the M23C6 and the M6C consists mainly of Cr and Mo carbides. Solidus-temperature is 1262°C, liquids-temperature is 1348°C.

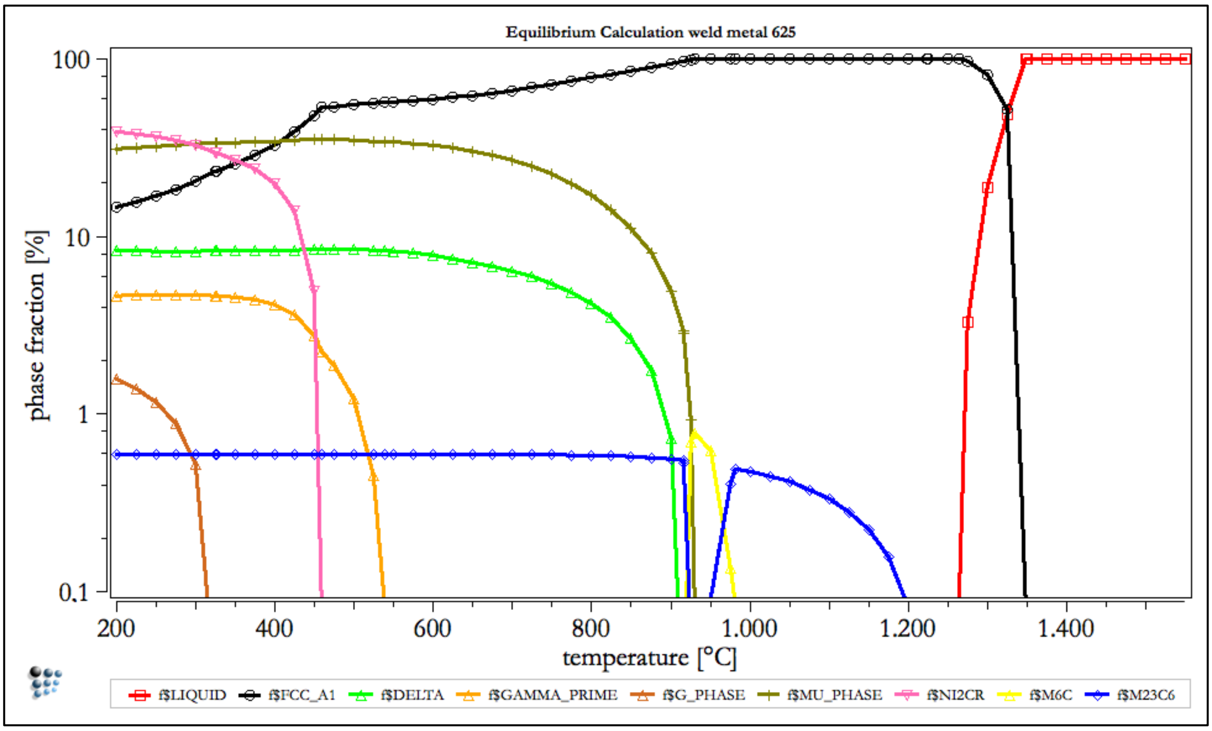


FIGURE 43: PHASE FRACTION PLOT WELD METAL 625

The weld metal alloy 625 of the performed weld test will differ from this calculation, due to a high cooling rate, which is not taken into consideration for this equilibrium calculations. It can be assumed, that maybe not all phases or precipitates will appear during solidification. For example to form the delta-phase it needs some hours at a dedicated temperature (see 4.4.3).

The final equilibrium phase fraction of weld metal 625 at 200°C are calculated by MatCalc as Table 18 shows.

TABLE 18: EQUILIBRIUM COMPOSITION MATCALC WELD METAL 625 (AT 200°C)

Phases	Phase fraction [%]
MU	31
FCC_A1	14
Delta	8
Gamma_prime	4,5
G_phase	1,6
M23C6	0,6
Matrix	rest

Table 19 shows the calculated phase transition temperatures by MatCalc.

TABLE 19: EQUILIBRIUM PHASE TRANSITION TEMPERATURES WELD METAL 625

Phase transition	Temperature [°C]
Solidus	1262
Liquids	1348

6 RESULTS AND DISCUSSION

In this chapter all results from the destructive and non-destructive tests are listed and discussed.

6.1 TENSILE TEST RESULTS

Figure 44: Layout tensile test specimen TIG/SMAW and Figure 45: Layout tensile test specimen EBW shows the layout of the tensile test specimen cut-out position rectangular to the weld. The specimens are machined as defined in DIN 50125 (see chapter 5.5.1 Tensile Test).

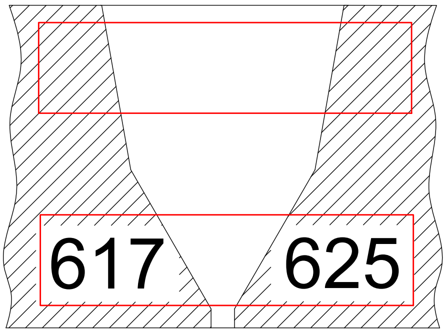


FIGURE 44: LAYOUT TENSILE TEST SPECIMEN TIG/SMAW – TOP AND ROOT OF THE WELD

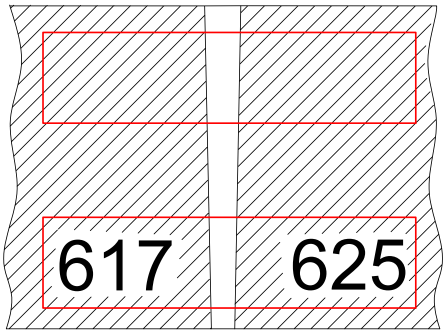


FIGURE 45: LAYOUT TENSILE TEST SPECIMEN EBW – TOP AND ROOT OF THE WELD

In Table 20: Tensile test results - tensile strength [MPa] are shown. EBW joint shows better results than TIG/SMAW joint. PWHT condition results are lower as AW condition results. The fracture position of the tensile test specimen is in the base material of alloy 617. Nevertheless all different specimens passed the welding procedure testing, as the required minimum tensile strength is 400 MPa.

TABLE 20: TENSILE TEST RESULTS - TENSILE STRENGTH [MPA]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
top	609	414	581	475
middle	-	451	-	-
bottom	685	489	565	400

In Figure 46: Tensile-test specimen TIG/SMAW overview, the fractured specimens are shown. The fracture is in the area of the alloy 617 base metal, which shows a ductile behavior, due to the high necking, which is irregular.

FIGURE 46: TENSILE-TEST SPECIMEN TIG/SMAW OVERVIEW – FRACTURE IN THE ALLOY 617 BASE METAL

FIGURE 47: TENSILE-TEST SPECIMEN TIG/SMAW DETAIL

In Figure 47: Tensile-test specimen TIG/SMAW detail, the fracture surface can be seen in more detail.

6.2 NOTCHED BAR IMPACT TEST RESULTS

The specimens are machined as defined in ÖNORM EN 10045-1 (see chapter 5.5.2 Notched-bar impact-bending Test (Charpy-V Test)). They were taken out from the fusion line of alloy 617 and alloy 625 as well as from the weld metal alloy 625 and the EBW fusion zone, see Figure 48: Layout specimen cut-out Charpy-V TIG/SMAW and Figure 49: Layout specimen cut-out Charpy-V EBW.

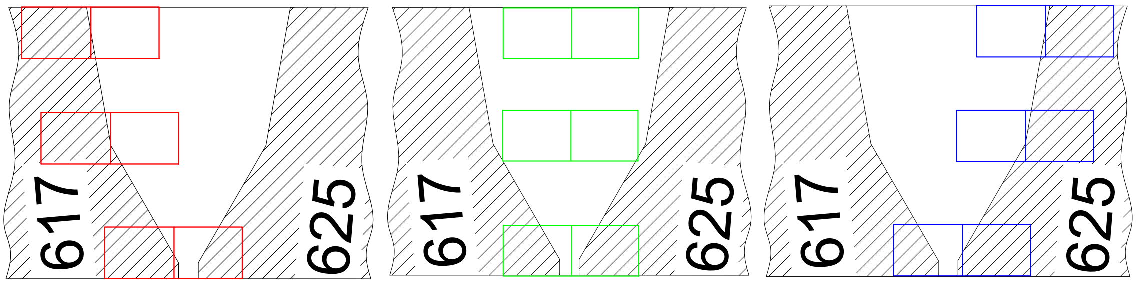


FIGURE 48: LAYOUT SPECIMEN CUT-OUT CHARPY-V TIG/SMAW

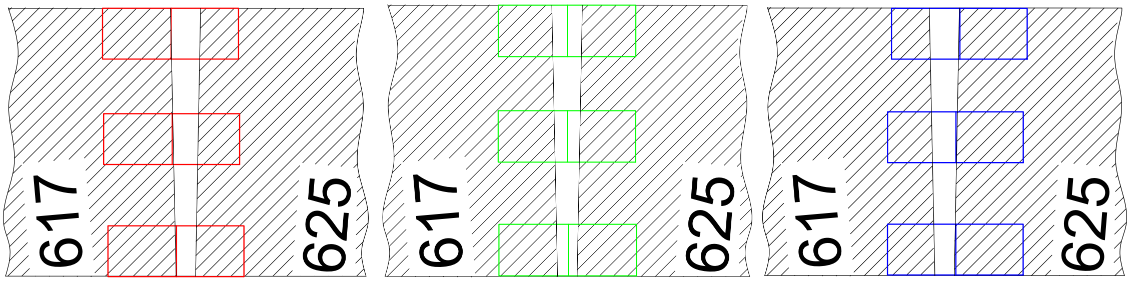


FIGURE 49: LAYOUT SPECIMEN CUT-OUT CHARPY-V EBW

In the following tables (Table 21 to Table 24) the results of the notched bar impact tests are listed for as welded (aw) and post weld heat treatment (pwht).

TABLE 21: CHARPY-V TEST RESULTS WELD METAL [J]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
top	214	-	75	50
middle	232	-	75	47
bottom	208	-	134	91

TABLE 22: CHARPY-V TEST RESULTS ALLOY625 [J]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
top	338	-	200	97
middle	372	-	148	105
bottom	357	-	205	86

TABLE 23: CHARPY-V TEST RESULTS ALLOY617 [J]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
top	300	-	40	40
middle	289	-	38	33
bottom	321	-	61	37

In Table 24: Charpy-V test results average values [J], of the particular tests are listed. The average value is the arithmetic mean value of top, middle and bottom values of each result set. Not all the tests passed the required minimum value of 50 J as it is demanded from customer for this application. Similar to the tensile tests, in this case the EBW specimens show better results too.

TABLE 24: CHARPY-V TEST RESULTS AVERAGE VALUES [J]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
weld metal	218	-	95	63
alloy 625	355	-	184	96
alloy 617	303	-	46	36

In Figure 50: Charpy-V test specimen fracture surfaces are shown. The fractures are either brittle fractures (e.g. SMAW alloy 617) as seen on the right side or ductile fractures (e.g. EBW specimen) as seen on the left side.

FIGURE 50: CHARPY-V TEST SPECIMEN FRACTURE SURFACES

6.3 MACROSCOPY AND HARDNESS TEST RESULTS

In this chapter an overview of the hardness test results is given. All detailed results can be found in the appendix.

The Vickers hardness HV10 was performed on weld cross sections. At the top and the middle of the EBW aw fusion zone a hardness increase from approx. 160 to 220HV10 appears. The bottom of the weld shows not that increase in hardness. The hardness lines can be seen in Figure 51.

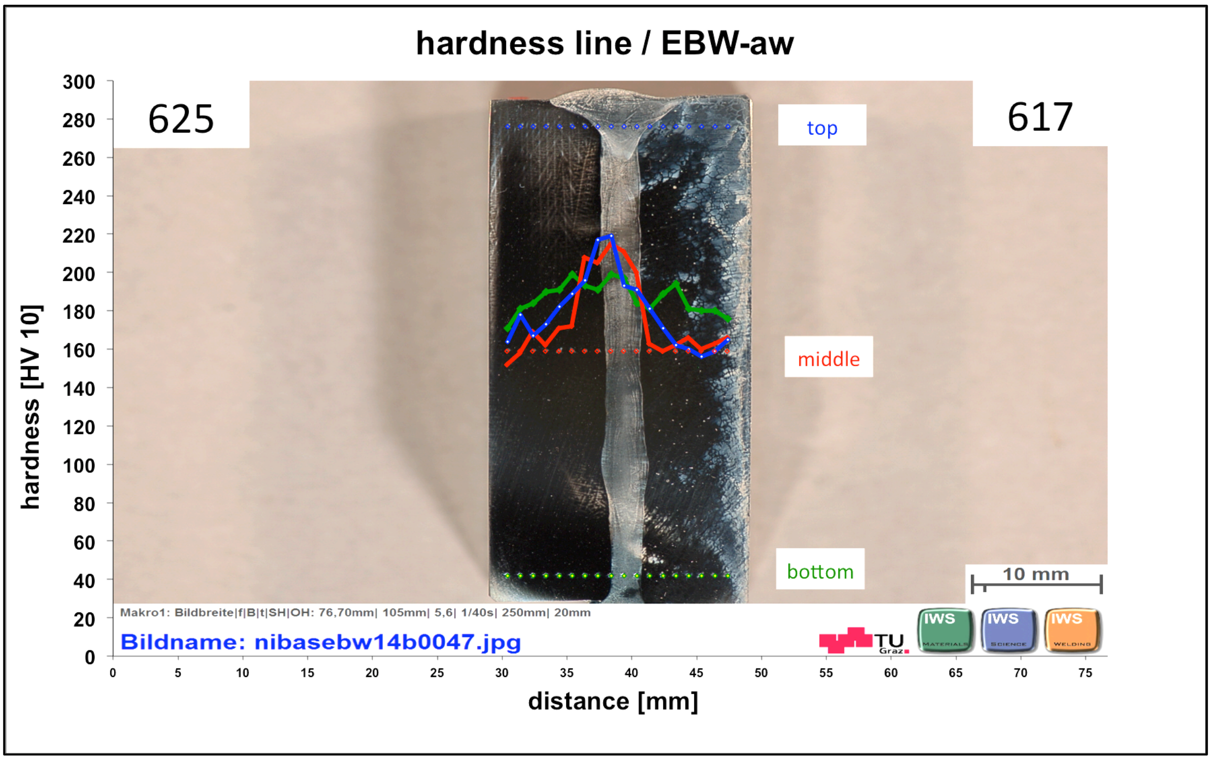


FIGURE 51: HARDNESS LINE EBW-AW

In Figure 52 the Vickers Hardness HV10 of the TIG / SMAW is shown. In the alloy 625 weld metal the hardness increases from approximately 160 to 280 HV10. The hardness in the base alloy 625 is below the weld metal 625. The hardness in the base alloy 617 is as well below the hardness of weld metal 625. The maximum hardness level of approximately 280 HV10 is for the three different hardness lines almost the same.

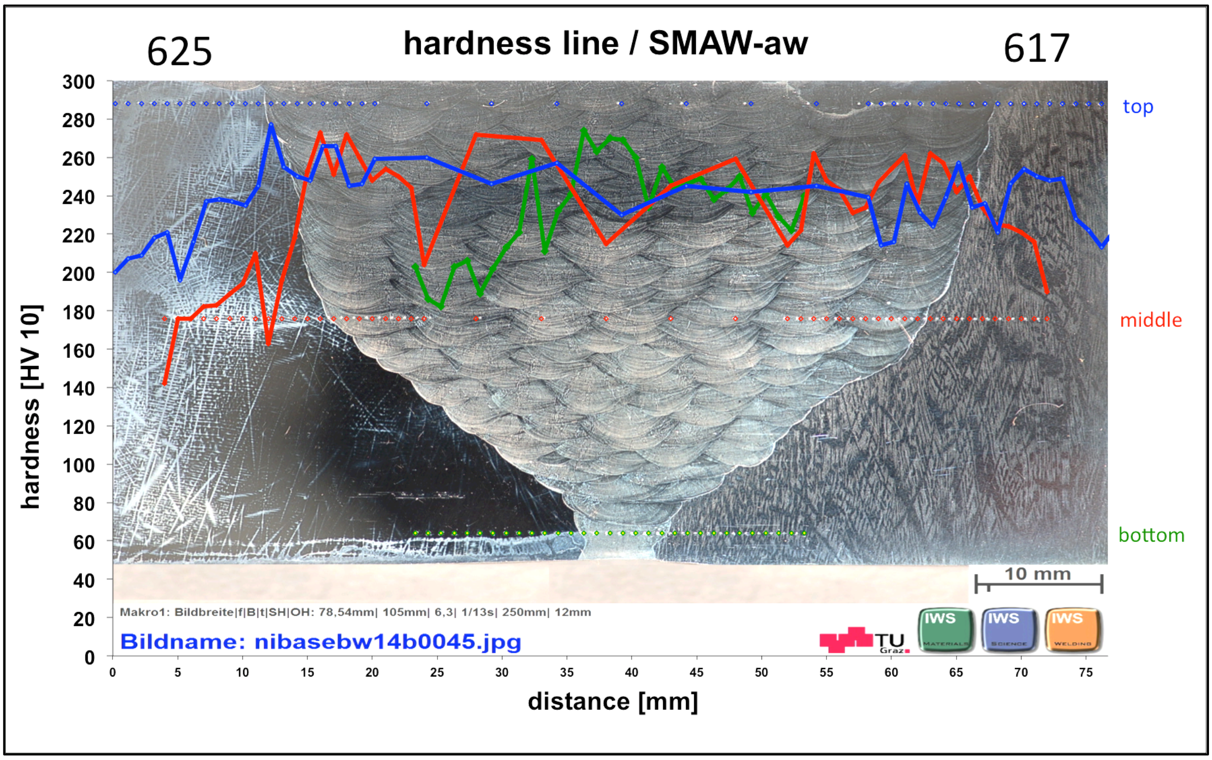


FIGURE 52: HARDNESS LINE SMAW-AW

After PWHT the hardness for weld metal alloy 625 decreases slightly (280 to 260 HV10) in comparison to “as-welded” state. The hardness in the base alloy 625 is below the hardness in the weld metal 625. The hardness in base alloy 617 is higher than the hardness in base alloy 625. The maximum hardness level of approximately 260 HV10 inside the weld metal is for the three different hardness lines almost the same. See Figure 53 for the Vickers Hardness HV10 of TIG / SMAW for PWHT state.

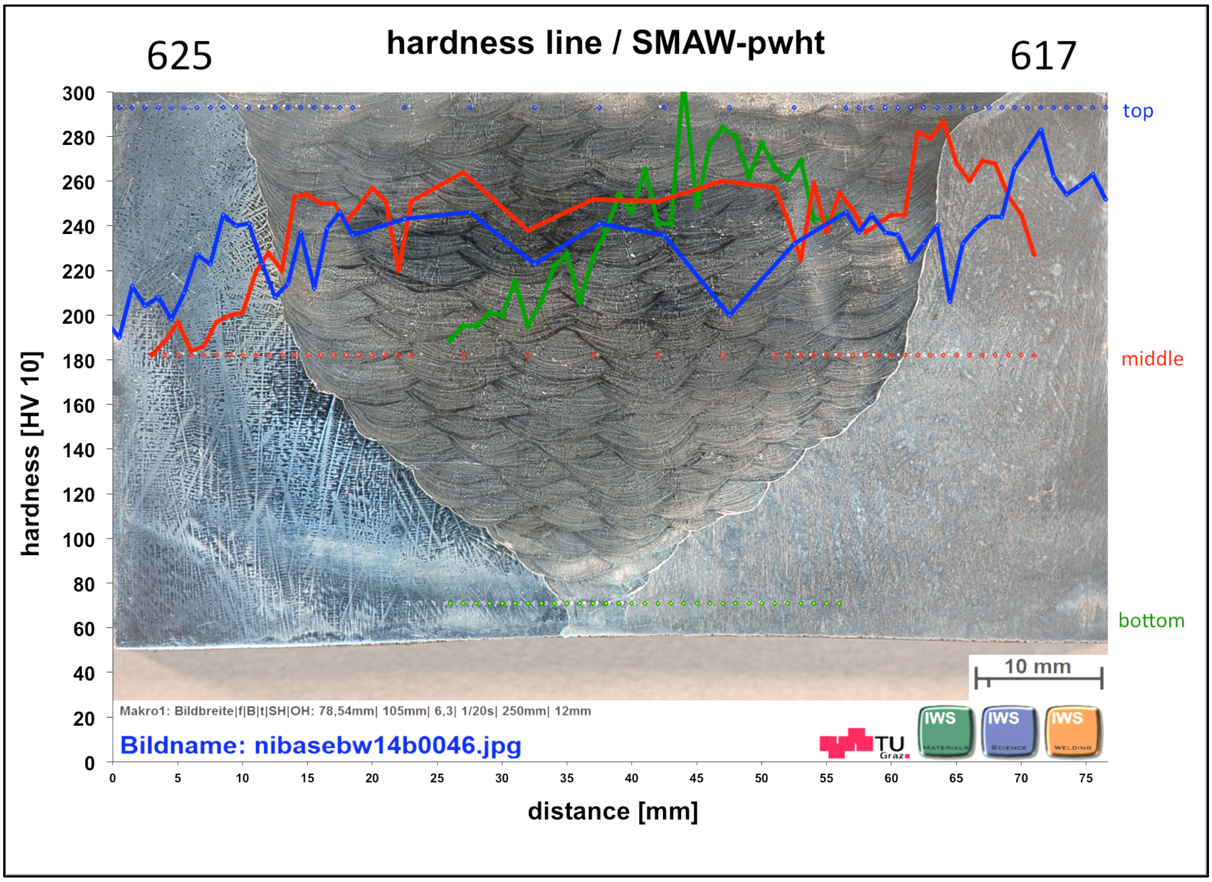


FIGURE 53: HARDNESS LINE SMAW-PWHT

In Table 25: hardness test average values [HV10] it can be seen, that hardness values differs between EBW and SMAW. The average values of EBW are around 180 HV10; whereat average values of SMAW are around 230 HV10. Nevertheless hardness differences between as welded and post weld heat treatment are quite small.

TABLE 25: HARDNESS TEST AVERAGE VALUES [HV10]

	EBW-aw	EBW-pwht	SMAW-aw	SMAW-pwht
top	179	-	236	232
middle	175	-	229	239
bottom	186	-	232	239

6.4 LIGHT OPTICAL MICROSCOPY (LOM) ANALYSES

This chapter gives an overview about the microstructure of the different welding specimens in Light Optical Microscopy (LOM). It is divided into the results of EBW-aw (as welded) test specimen and SMAW-aw and SMAW-pwht (post weld heat treatment) test specimen.

6.4.1 EBW-AW

At the following pages some exemplarily figures shows occurrences in the microstructure. In Figure 54 the fusion line of the welding joint at the side of alloy 625 base metal can be seen. The blue frames mark two precipitates. According to literature [14] these could be Cr, Mo or Ti precipitates, like Carbides, Nitrides or Carbo-Nitrides; see SEM analysis in chapter 6.5. The weld metal shows dendritic structure (dark and bright phase) and a thin, dark emerging layer at the fusion line.

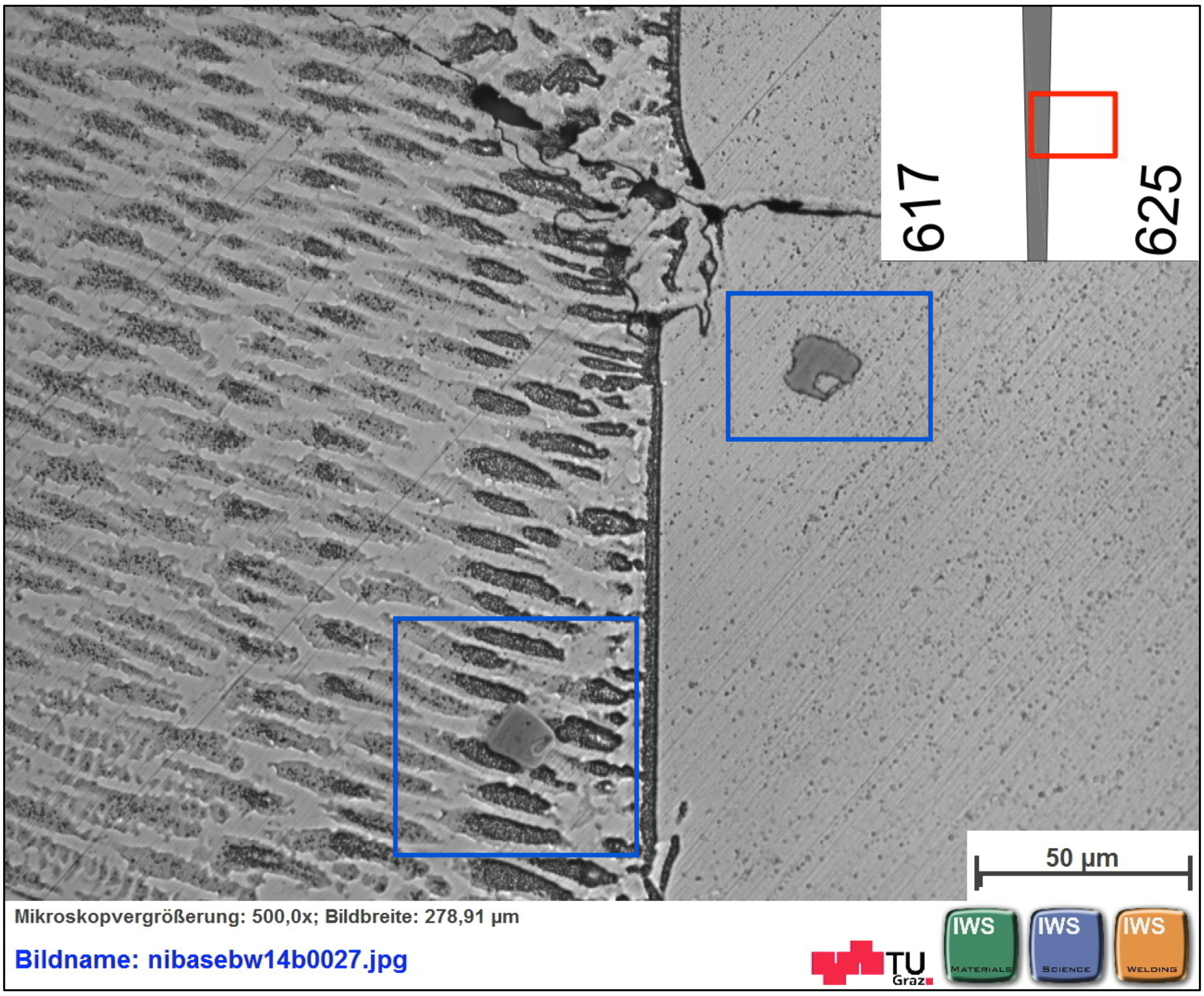


FIGURE 54: LOM IMAGE EBW-AW 625 FUSION LINE (V2A ETCHANT)

In Figure 55 the welding joint fusion line at the side of base metal alloy 617 is shown. The blue frame again marks some precipitates, which again can contain (according to literature [42]) Cr, Mo or Ti.; see chapter 6.5. The weld metal shows a dendritic structure and a white emerging thin layer at the fusion line.

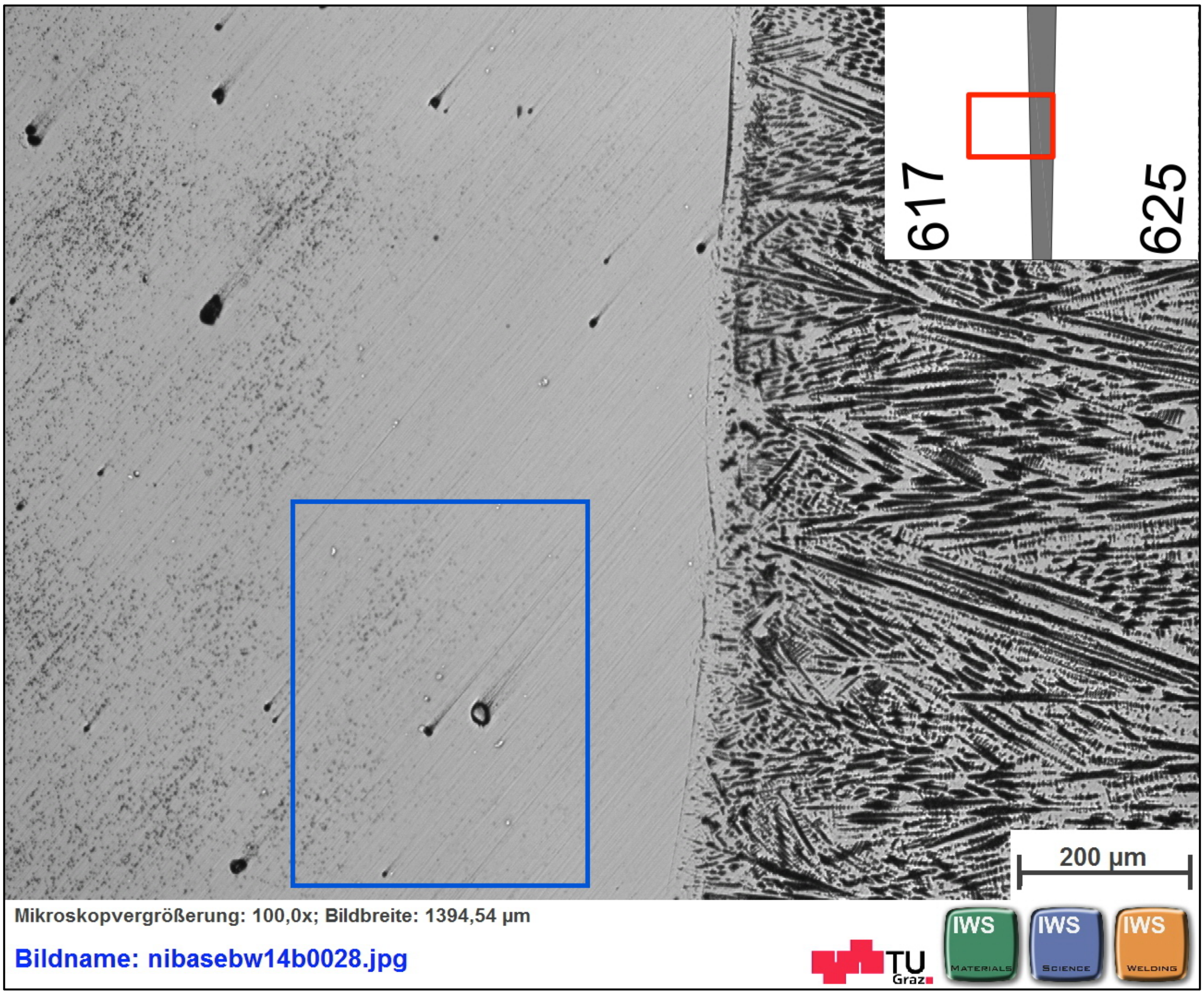


FIGURE 55: LOM IMAGE EBW-AW 617 FUSION LINE AND PRECIPITATES (V2A ETCHANT)

6.4.2 SMAW-AW

In Figure 56 a cross-section of the weld metal alloy 625 of SMAW can be seen. Here dendritic structures in different orientations appear and every layer of the welding joint is visible.

FIGURE 56: LOM IMAGE SMAW-AW WELD METAL ALLOY 625 (V2A ETCHANT)

In Figure 57 the fusion line of base metal alloy 625 and the weld metal alloy 625 can be seen. On the right side the coarse grain size and the primary structure of casted alloy 625 is visible as well as some flow lines. On the left side the layers of the weld metal are observable.

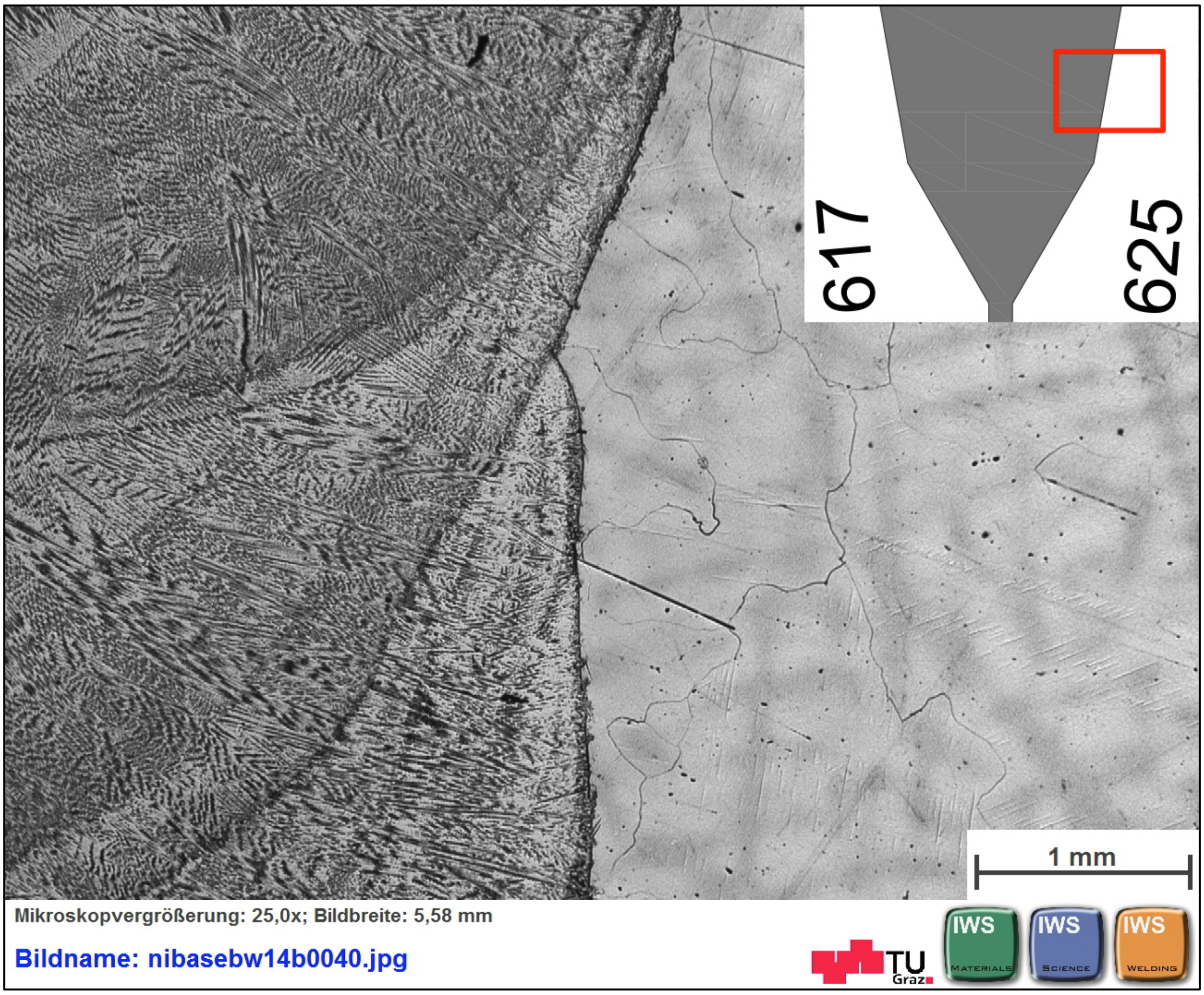


FIGURE 57: LOM IMAGE SMAW-AW FUSION LINE ALLOY 625 – WELD METAL (V2A ETCHANT)

In Figure 58 the fusion line between alloy 625 and the weld metal is exhibited in detail. It shows, that there are some precipitates (analyzed in chapter 6.5.) in the base material of alloy 625 (blue frames).

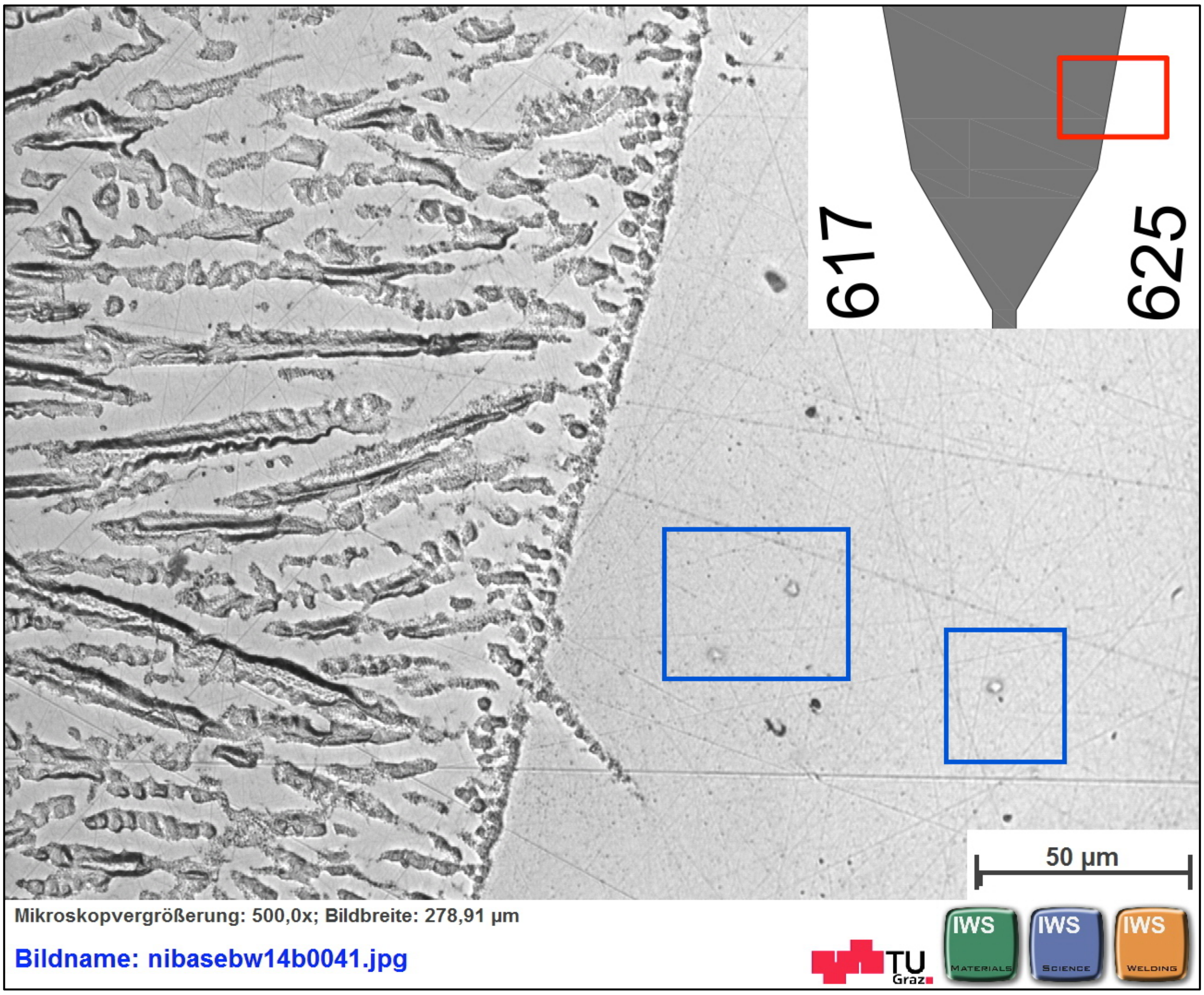


FIGURE 58: LOM IMAGE SMAW-AW FUSION LINE ALLOY 625 - WELD METAL (V2A-ETCHANT) - DETAIL

In Figure 59 the fusion line between alloy 617 and the weld metal is shown. Here the fine grain size of forged alloy 617 and the dendritic structure of the weld metal can be observed.

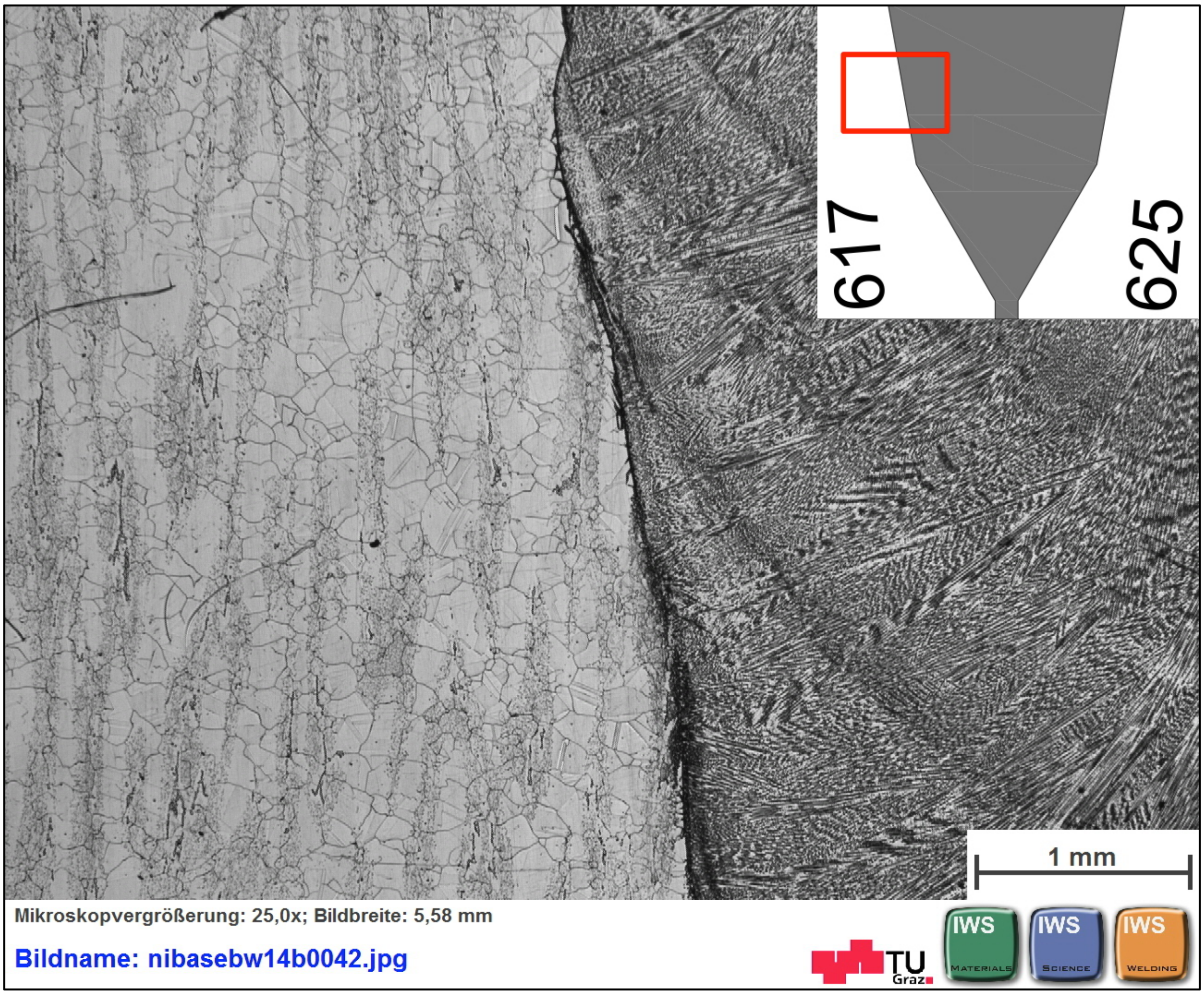


FIGURE 59: LOM IMAGE SMAW-AW FUSION LINE ALLOY 617 – WELD METAL

In Figure 60 the fusion line between alloy 617 and weld metal is shown in detail. Again there are some precipitates marked with blue frames, which will be analyzed in chapter 6.5.

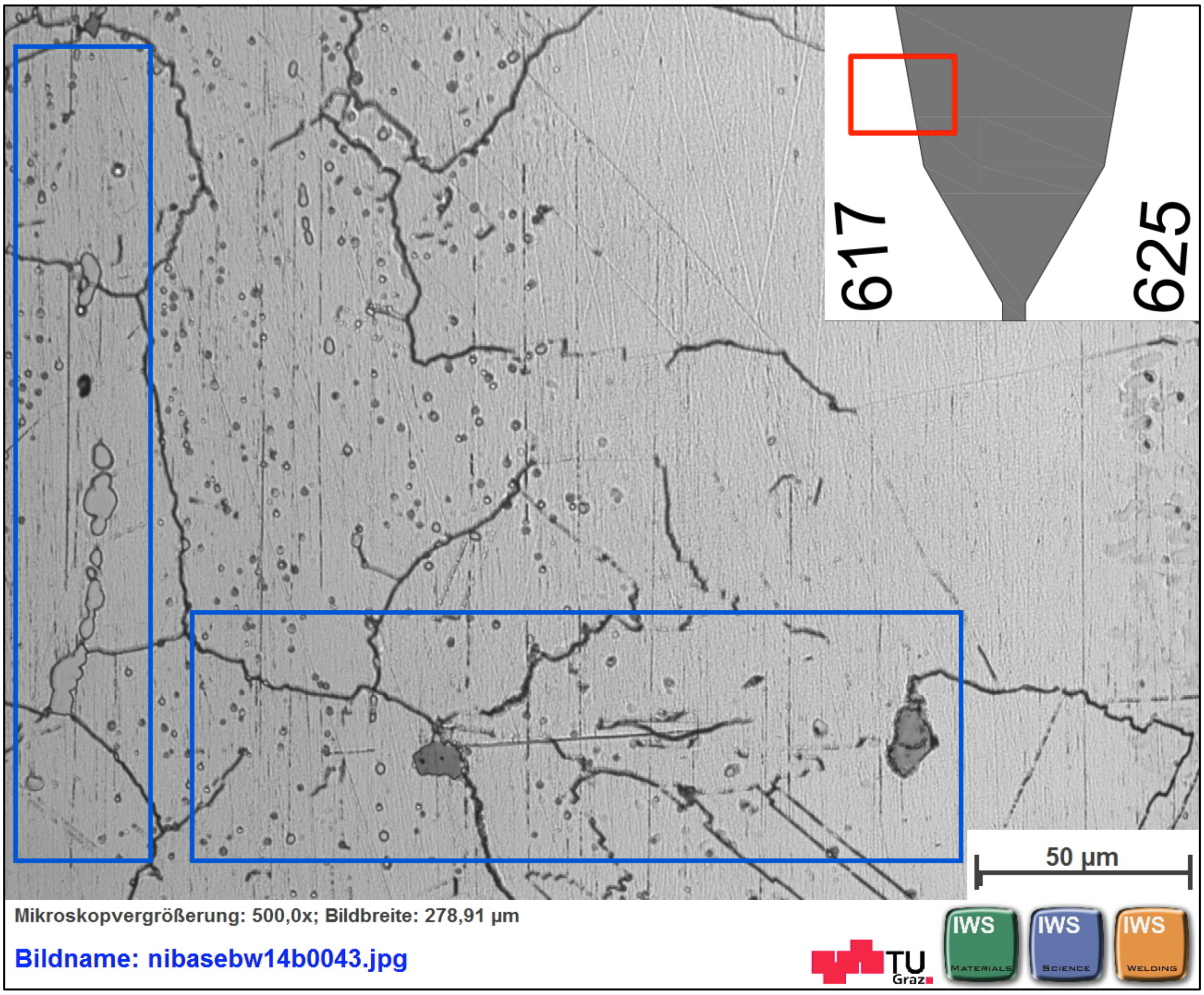


FIGURE 60: LOM IMAGE SMAW-AW FUSION LINE ALLOY 617 – WELD METAL - DETAIL

6.4.3 SMAW-PWHT

The heat treatment was done at VAGT as followed:

Heating rate:	50°C/h
Temperature:	800°C
Holding period:	4h
Cooling:	at air environment

In the post weld heat treatment (PWHT) state it is apparent that there are less precipitates in the base metal alloy 625 than in the as welded (AW) state. This is due to the diffusion through microstructure during the heat treatment.

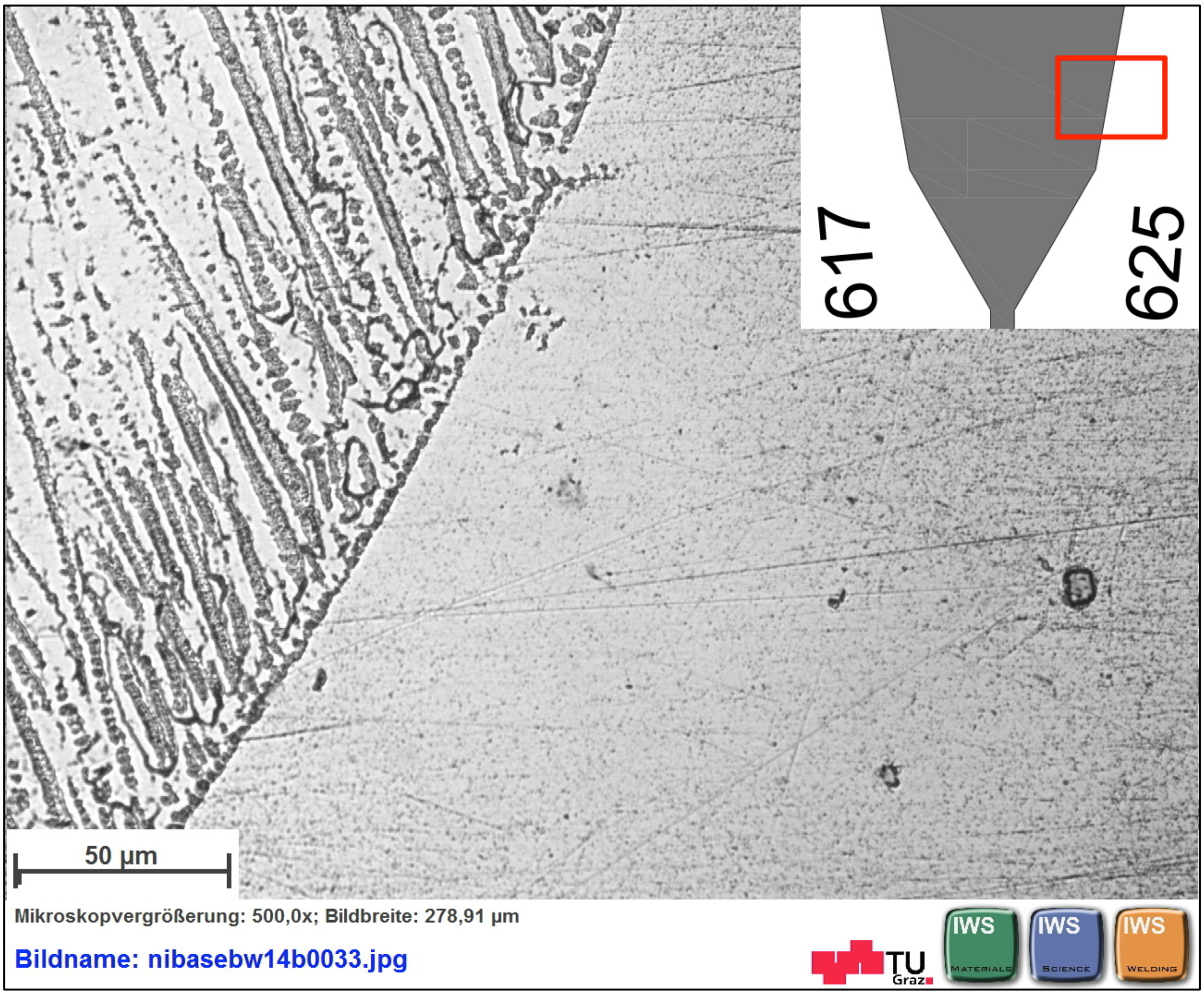


FIGURE 61: LOM IMAGE SMAW-PWHT FUSION LINE ALLOY 625 - WELD METAL – DETAIL (ETCHANT V2A)

In Figure 62 the fusion line between alloy 617 and the weld material after PWHT can be seen. Again, the fine grain size of forged alloy 617 and the dendritic microstructure of the weld metal are well visible. No change of the microstructure due to the PWHT can be found in LOM.

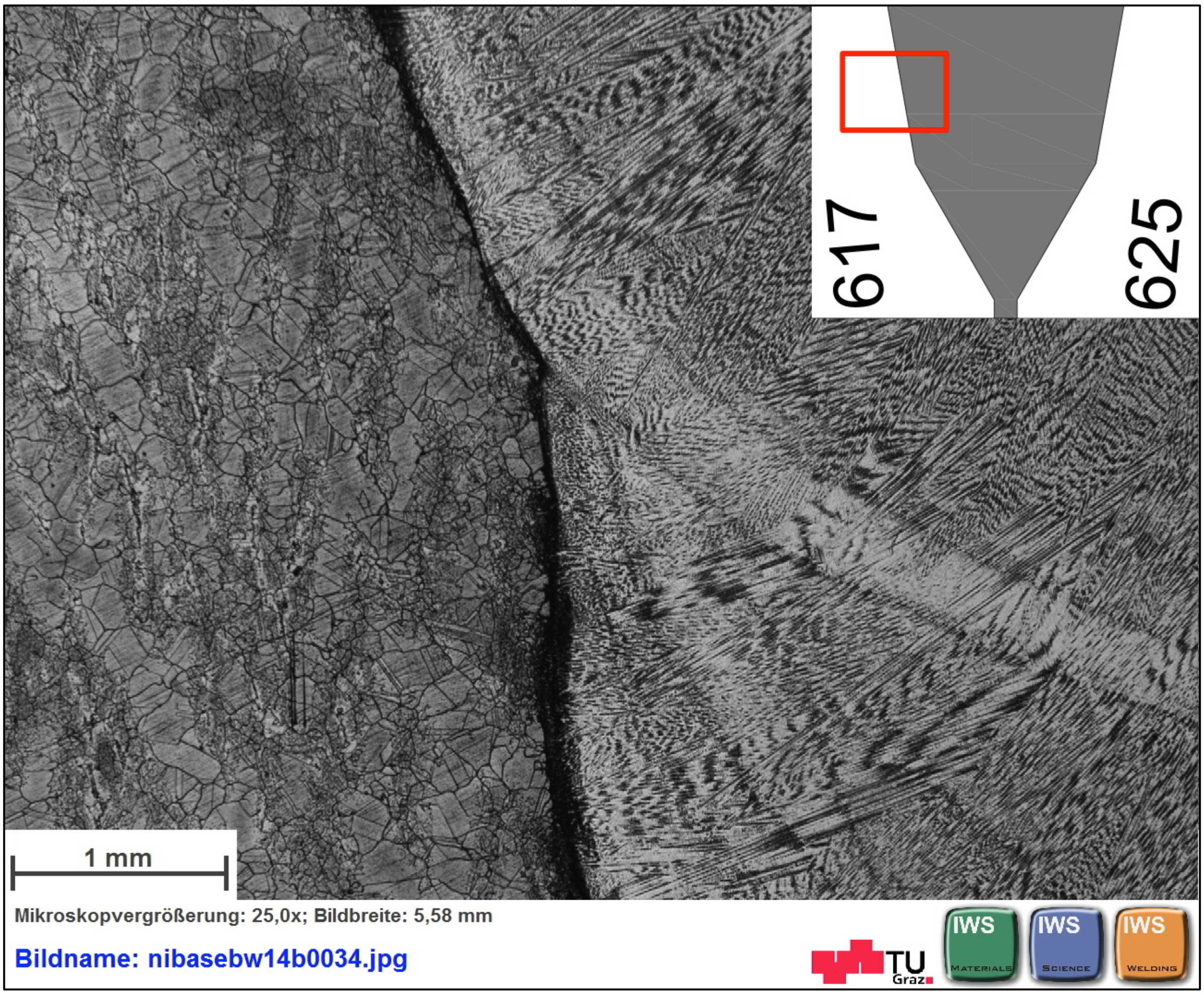


FIGURE 62: LOM IMAGE SMAW-PWHT FUSION LINE ALLOY 617 – WELD METAL – DETAIL (ETCHANT V2A)

In Figure 63 the fusion line of alloy 617 and the weld material is shown. It is apparent that there are less precipitates after PWHT due to the diffusion through microstructure during heat treatment.

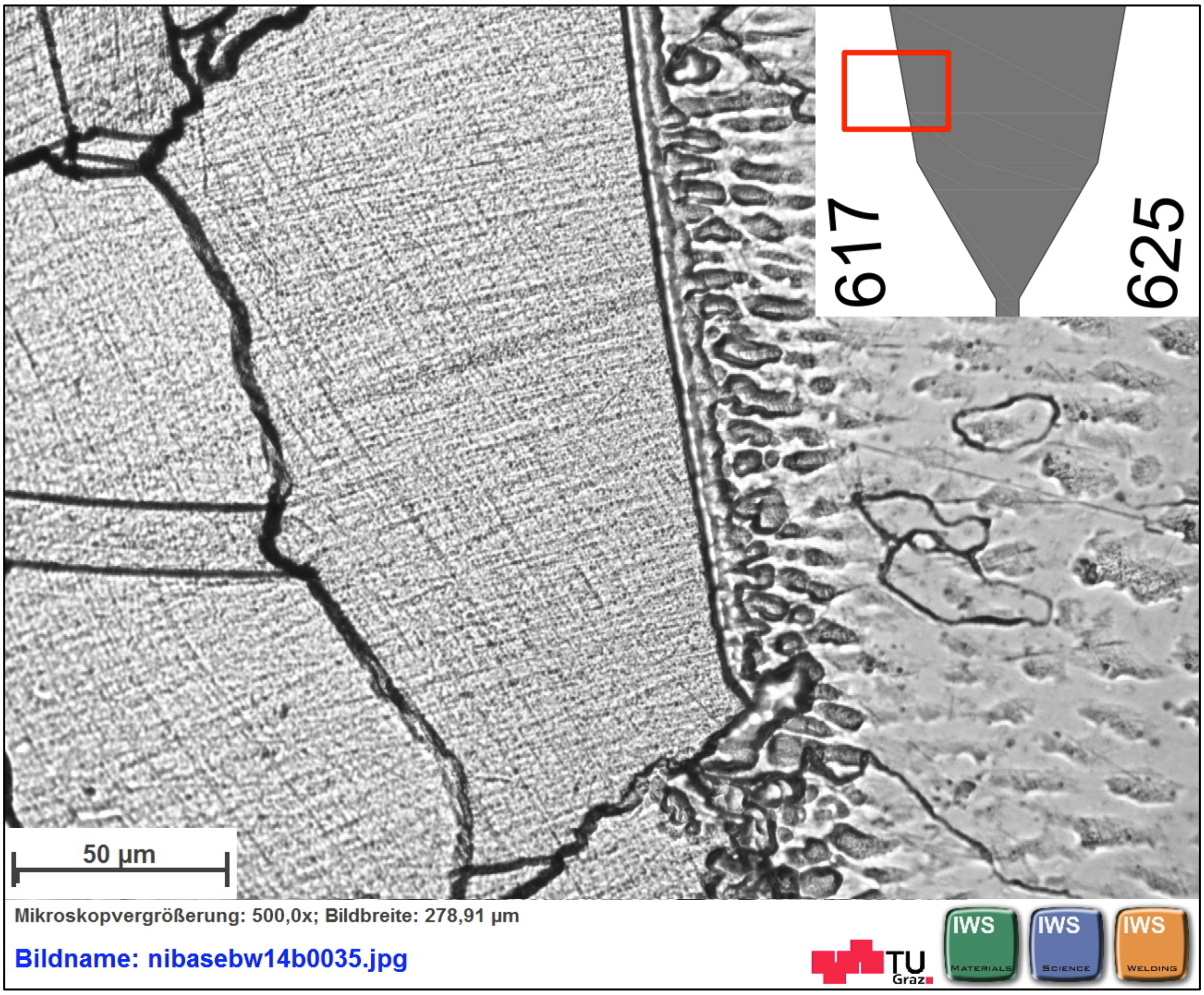


FIGURE 63: LOM IMAGE SMAW-PWHT FUSION LINE ALLOY 617 – WELD METAL – DETAIL (ETCHANT V2A)

6.5 SCANNING ELECTRON MICROSCOPE (SEM) AND EDX ANALYSES

This chapter deals with the SEM analyses of the precipitates in the base materials and the weld metal. The SEM allows the determination of different elements by energy dispersive X-ray analyses (EDX), i.e. elements with different atomic numbers create different amount of characteristic x-ray radiation due to electron jumps between atomic orbitals caused by the incident electron beam of the SEM. Hence element distributions can be visualized a by a so-called mapping, as the intensity of the x-rays is proportional to the element concentrations.

This SEM examination was only done for the SMAW-aw specimen, because of time and cost matters. Moreover for the other specimens the SEM investigation was not highly required, as a qualitative prediction of the type of precipitates is also possible with the performed LOM analyses (see chapter 6.4).

6.5.1 SEM SMAW-AW ALLOY 617 BASE METAL

In Figure 64 the precipitates in the base metal of alloy 617 can be seen as overview in the SEM backscattered electron-imaging mode (BE mode). The blue frame marks the area, which was investigated in detail. In Figure 65 the details at higher magnification in BE mode is shown.

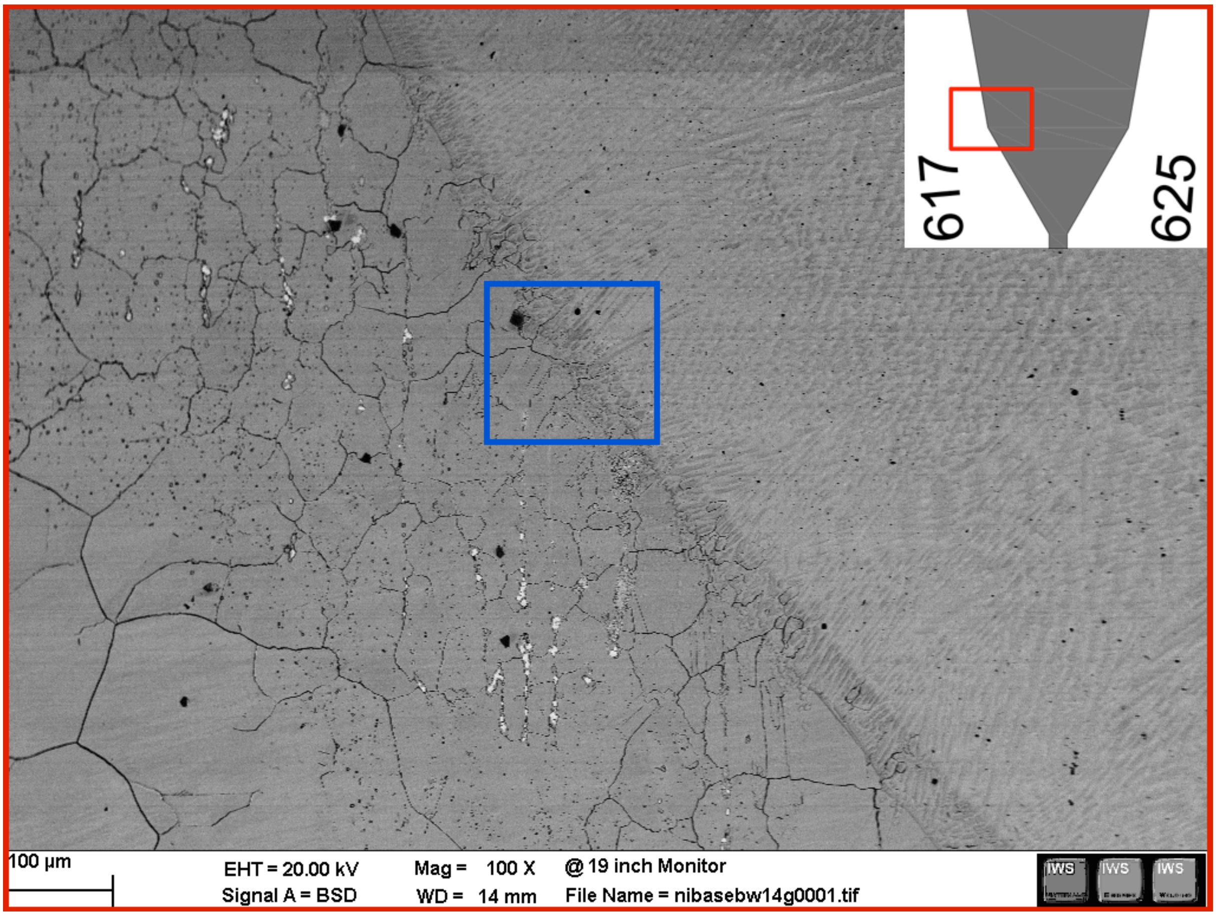


FIGURE 64: SEM IMAGE (BE MODE) – FUSION LINE ALLOY 617-WELD METAL OVERVIEW

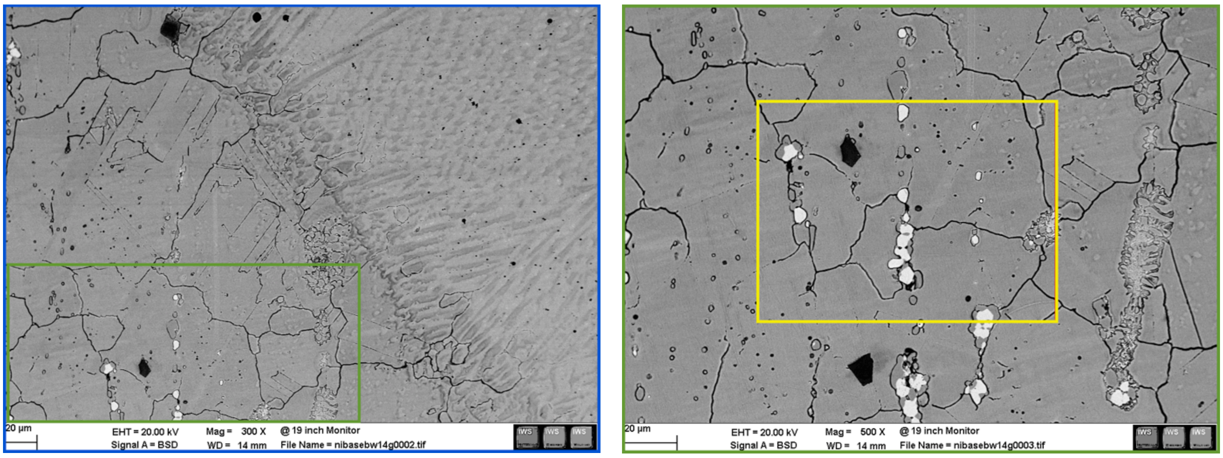


FIGURE 65: [L] SEM IMAGE (BE MODE) FUSION LINE ALLOY 617 - WELD METAL, [R] BASE METAL

On the left side in Figure 66 the SEM image of alloy 617 base metal at a magnification of 1000x is shown, whereat white, gray and black appearing precipitates can be seen. The mapping on the ride hand side show that the polygonal precipitate contain Ti (Ti-Carbides or Ti-Carbo-nitrides, blue colored) and the rounded precipitates contain Cr and Mo (probably intermetallic, red and green colored).

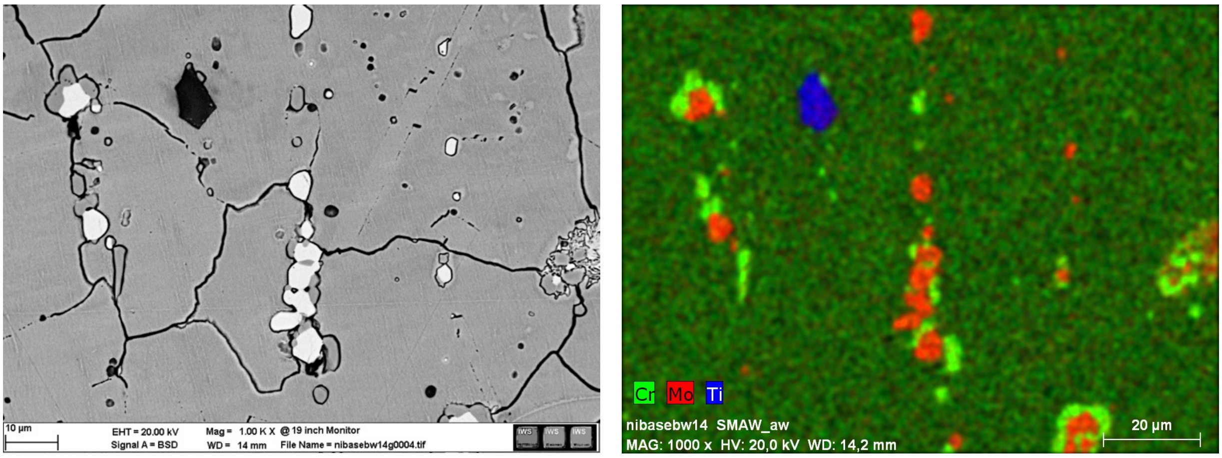


FIGURE 66: [L] SEM IMAGE (BE MODE) BASE METAL ALLOY 617, [R] CR-MO-TI MAPPING

In Figure 67 a so-called line-scan is shown. The peaks verify that the polygonal precipitate contain just Ti (C and N can not be detected with the present EDX system), i.e. probably Ti-Carbides or Ti-Carbo-nitrides. The rounded precipitates contain just Cr and Mo, i.e. probably Cr-Carbides (or Nitrides) and Mo-Carbides.

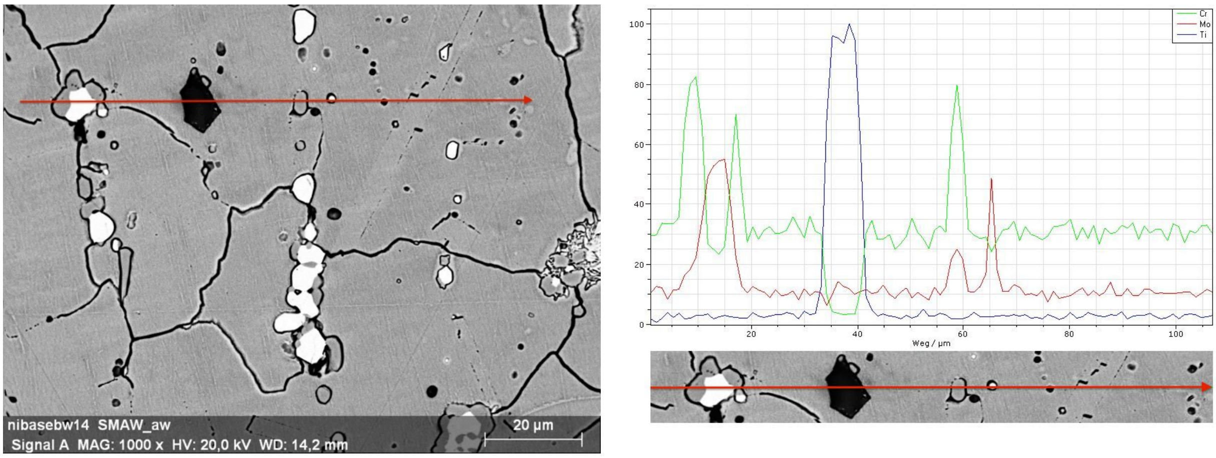


FIGURE 67: [L] SEM IMAGE (BE MODE) BASE METAL ALLOY 617, [R] LINE SCAN

6.5.2 SEM SMAW-AW WELD METAL

In Figure 68 an overview of the microstructure at the fusion line – the weld metal alloy 625 and the base metal alloy 617 can be seen. The blue frame marks the area of the weld metal, which is investigated in detail, see Figure 69, whereat a typical orientated dendritic structures with low contrast differences are visible.

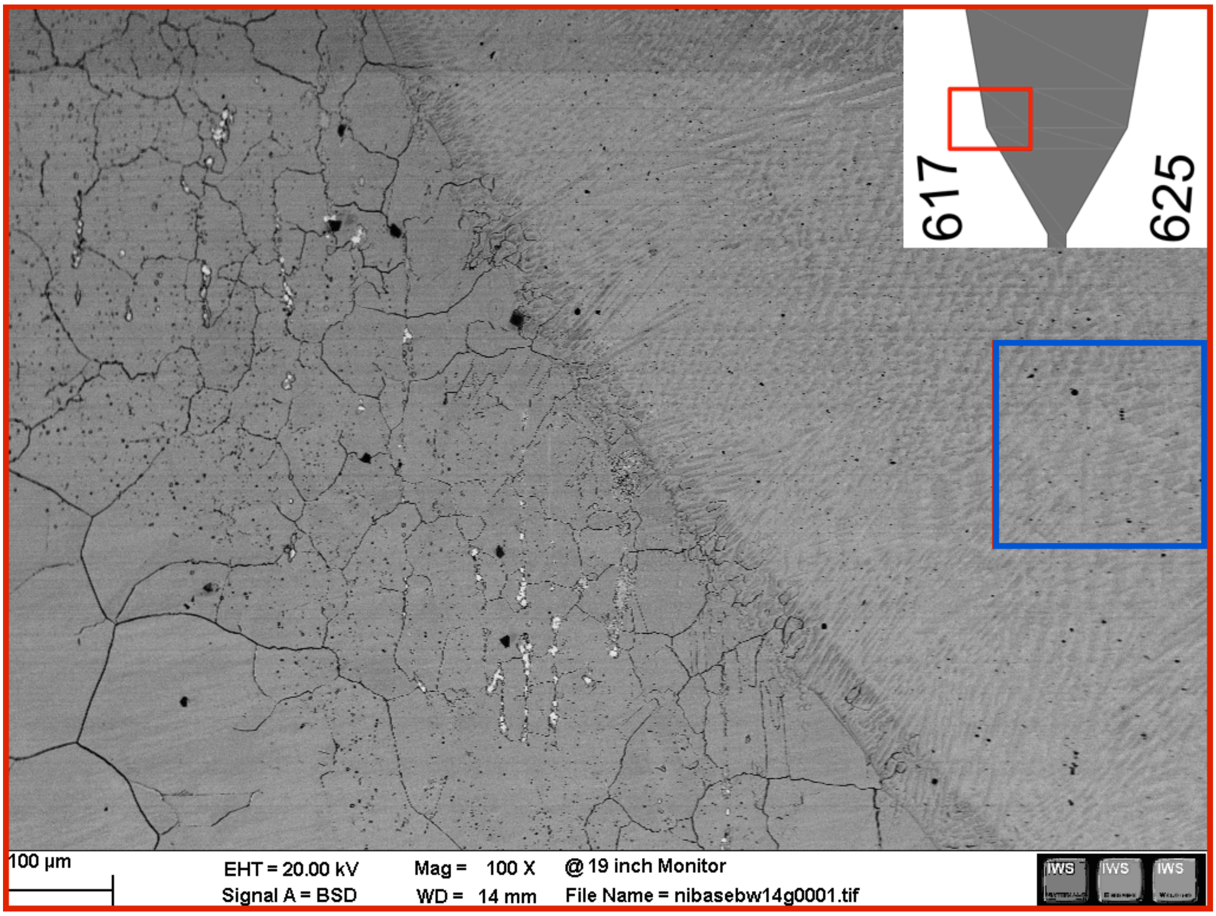


FIGURE 68: SEM IMAGE (BE MODE) – FUSION LINE ALLOY 617-WELD METAL OVERVIEW

In Figure 70 on the left hand side many black appearing micro pores and micro slag inclusion as well as white appearing sub-micron precipitates can be observed in the dendritic microstructure. The mapping shows a homogenous distribution of Cr and Mo, i.e. no precipitations of this type exist.

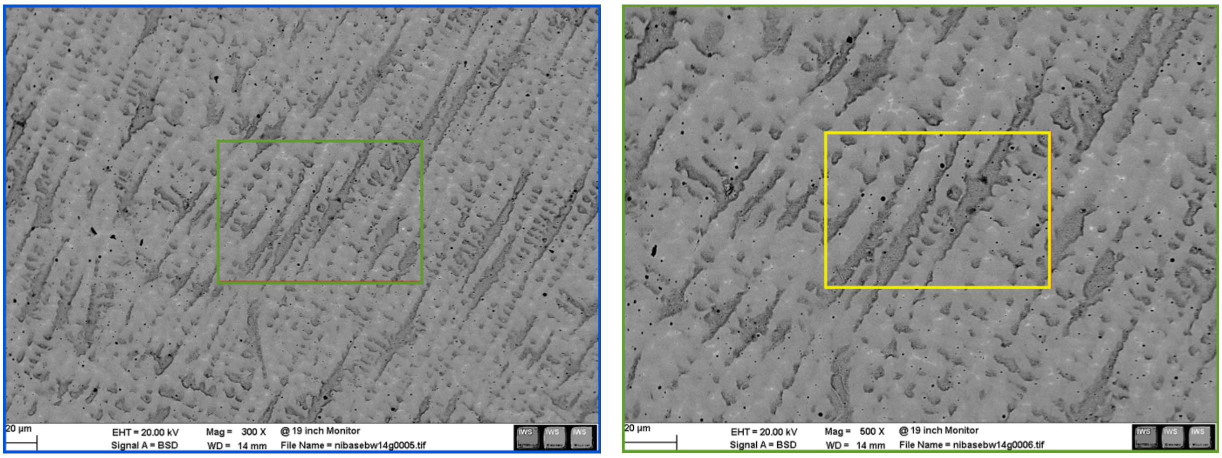


FIGURE 69: SEM IMAGES (BE MODE) WELD METAL DETAILS – DENDRITIC STRUCTURE

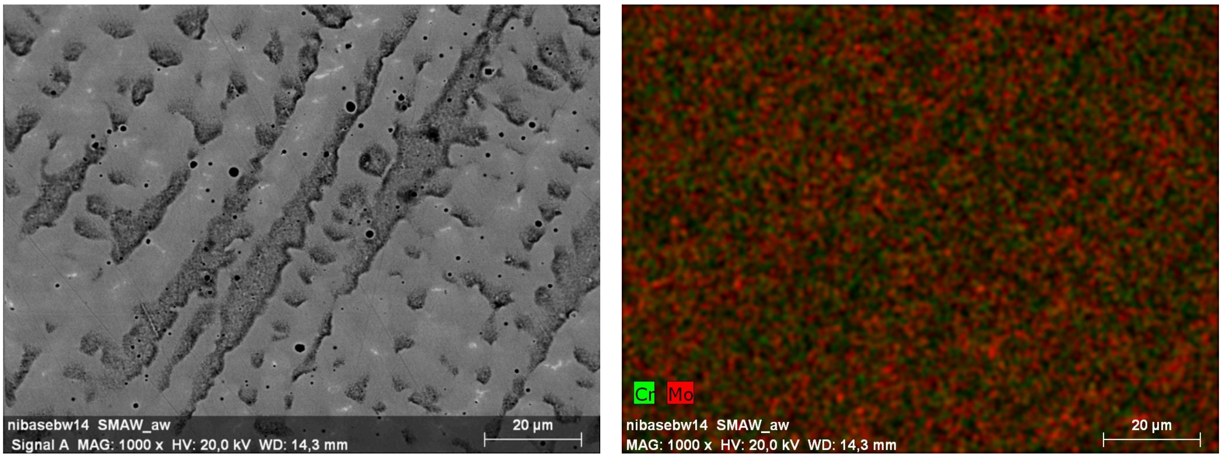


FIGURE 70: [L] SEM IMAGE (BE MODE) WELD METAL ALLOY 625, [R] CR-MO MAPPING

6.5.3 SEM SMAW-AW ALLOY 625 BASE METAL

In Figure 71 an overview of the microstructure at the fusion line - the weld metal alloy 625 and the base metal alloy 625 is exhibited. The dendritic structure of the weld metal and the precipitation-free zone in the base metal besides micro pores and micro inclusions impurities from the casting process is visible. The blue frame marks the area, which is investigated in detail, see Figure 72, whereat nothing conspicuous could be found.

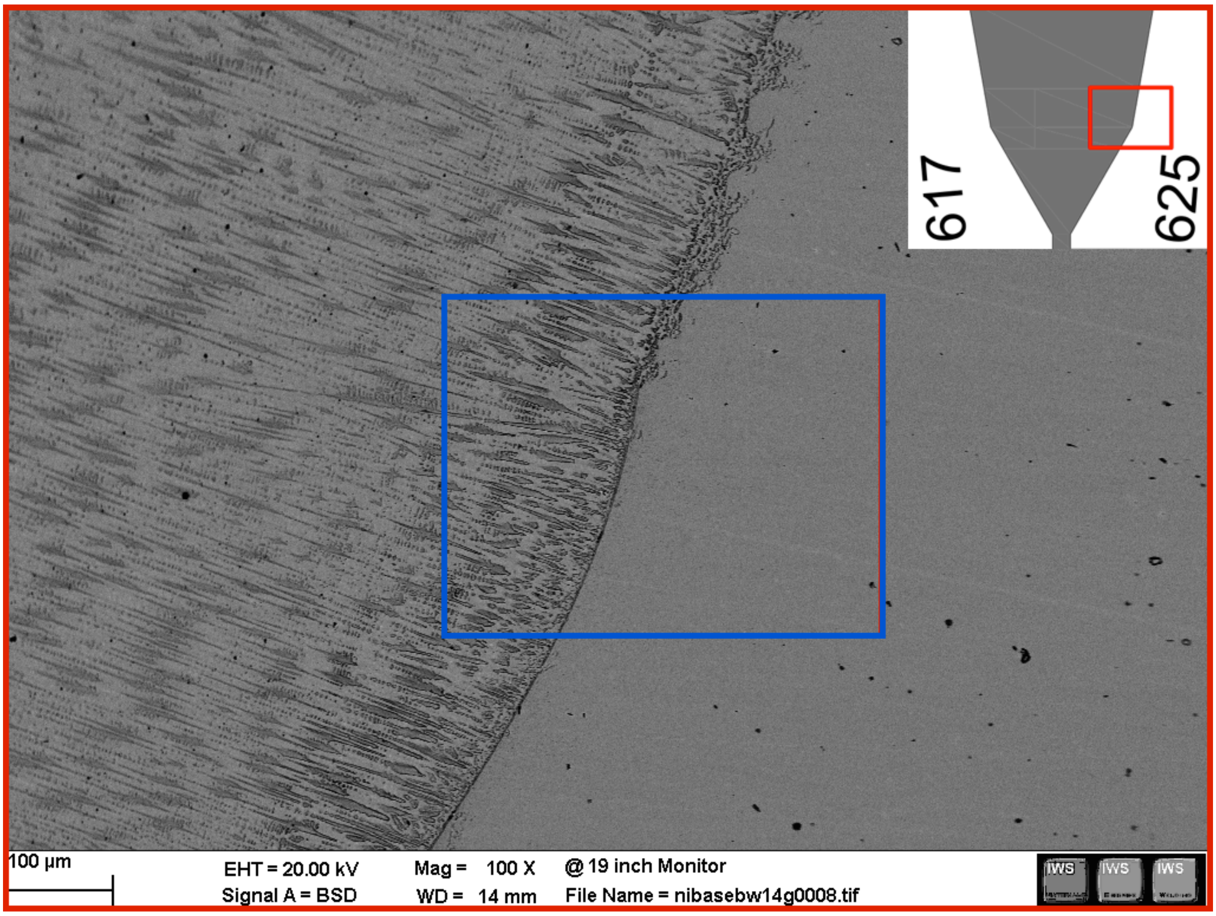


FIGURE 71: SEM IMAGE (BE MODE) – FUSION LINE ALLOY 625 - WELD METAL OVERVIEW

Figure 73 shows the fusion line in detail of alloy 625 and the similar weld metal alloy 625, whereat no Cr or Mo precipitates could be found, as can be seen in the mapping.

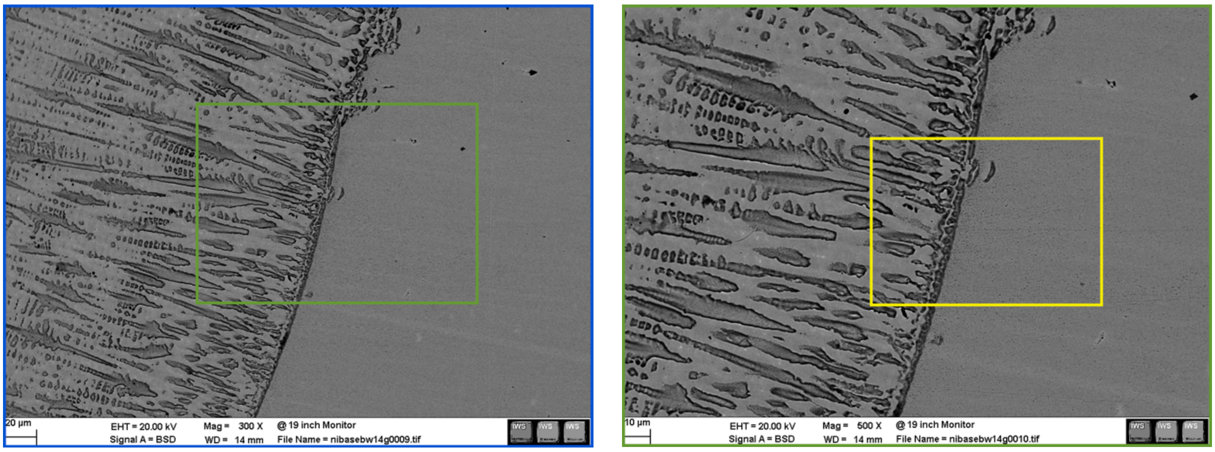


FIGURE 72: [L] SEM IMAGE (BE MODE) DENDRITIC STRUCTURE IN WELD METAL, [R] PRECIPITATION FREE ZONE IN BASE METAL

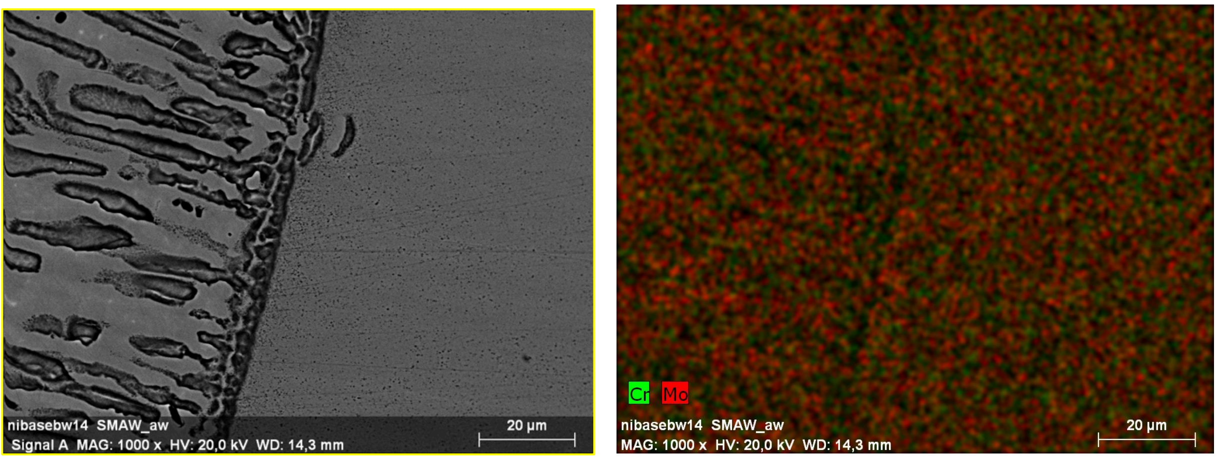


FIGURE 73: [L] SEM IMAGE (BE-MODE) FUSION ZONE, [R] CR-MO MAPPING

7 SUMMARY AND CONCLUSION

The dissimilar welding of alloy 625 and alloy 617 was successfully performed. Nevertheless only the electron beam welding (EBW) process achieved the required criteria for Welding procedure testing (ISO 15614-1, ISO 15614-11).

The shielded metal arc welding (SMAW) process - using TIG filler alloy 625 for the root passes and SMAW electrode alloy 625 for the filler and top passes – did not achieve all of the required criteria stated in the standards for Welding procedure testing. The values for notched bar impact test for alloy 617 were below the required limits.

Due to the SMAW heat in the base metal alloy 617 Cr and Mo as well as Ti precipitations are formed close to the fusion line. However their size and amount are supposed to be uncritical.

Nevertheless the EBW-process is favorable by means of mechanical properties and time. If the correct welding parameters are found for the EBW-process it is the more reliable and reproducible process, because there is no influence of the welder and of dusty welding environment. Another advantage of EBW is the welding without the usage of filler material.

On the other hand the biggest disadvantage of EBW is the requirement of a high-vacuum. So the work piece size is limited dependent on the size of the vacuum chamber.

MatCalc equilibrium calculations provide a good overview of phases and precipitates, which can occur in general for the every alloy. Furthermore for an exact simulation of phases and precipitates after welding (or during solidification) it would be necessary to perform a Scheil-Gulliver calculation instead an equilibrium calculation.

The post weld heat treatment (800°C for 4 hours) on the SMAW does not improve the material properties, so it is not necessary to conduct it.

8 OUTLOOK

The focus of this project was the weldability and especially the fulfillment of the welding procedure qualification record. Thus this thesis has no claim to completeness and there exist still open questions concerning the applicability for steam power plants with 700°C technology.

There was no investigation on the operational capability of this alloy 617 / alloy 625 welding joint by means of long-term creep tests. The evolution of the microstructure during exposure to high temperatures must be investigated. The next steps should be to perform some creep tests to gain some experience on the creep behavior.

9 LIST OF FIGURES

10 LIST OF TABLES

11 REFERENCES

[1] V. Knezevic, a. Schneider, and C. Landier, "Creep Behaviour of Thick-Wall Alloy 617 Seamless Pipes for 700°C Power Plant Technology," *Procedia Eng.*, vol. 55, pp. 240–245, Jan. 2013.

[2] B. Müller, "Preparing for a Fiery Future," pp. 33–34, 2008.

[3] voestalpine Böhler Welding, "Welding Solutions for Thermal Power Generation," 2013.

[4] C. Sommitsch, "Werkstoffkunde." TU-Graz, 2012.

[5] U. Heubner and J. Klöwer, *Nickelwerkstoffe und hochlegierte Sonderstähle*. 2009.

[6] F. Vollertsen and W. Blum, *Werkstoffeigenschaften und Mikrostruktur*. Carl Hanser Verlag München Wien, 1989.

[7] M. Prüfer, M. Möser, and N. Hütte, "Vorzeitiges Bauteilversagen durch lokalisiertes Korngrenzengleiten und duktile interkristalline Rissbildung – Relaxationsrissigkeit," vol. 25, pp. 1–13, 1980.

[8] C. EDUPACK, "lnconel 617," 2005.

[9] S. Schlegel, S. Hopkins, E. Young, J. Cole, T. Lillo, and M. Frary, "Precipitate Redistribution during Creep of Alloy 617," *Metall. Mater. Trans. A*, vol. 40, no. 12, pp. 2812–2823, Sep. 2009.

[10] J. Benz, "Aging of Alloy 617 at 650 and 750 ° C," no. January. 2013.

[11] C. Wiednig, "Electron Beam Welding Alloy 625." Master thesis TU-Graz, 2013.

[12] S. Metals, "INCONEL alloy 625," vol. 625, no. 2, pp. 1–18, 2013.

[13] B. Bezzola, "Mechanical and microscopic characterization of short term aged cast alloy 625." Master thesis Politecnico di Milano, TU-Graz, 2014.

[14] B. Berger, "Dissimilar Schweißen von (Konstruktionsschweißungen) NIBAS 625 mit warmfestem Cr-Stahl COST CB2," vol. Master the. Master thesis TU-Graz, 2011.

[15] J. N. D. J. C. Lippold, S. D. Kiser, *Welding Metallurgy and Weldability of Nickel-Base Alloys*. New Jersey: John Wiley & Sons, 2009.

[16] J. Mittra, S. Banerjee, R. Tewari, and G. K. Dey, "Fracture behavior of Alloy 625 with different precipitate microstructures," *Mater. Sci. Eng. A*, vol. 574, pp. 86–93, Jul. 2013.

[17] ThyssenKrupp, "Nicrofer 6020 hMo - alloy 625," no. 4118, 2007.

[18] DVS, *Internationaler Schweißfachingenieurlehrgang*. Gesellschaft für Schweißtechnik International mbH, 2008.

[19] O. T. L. Maurice Stewart, "Fabrication, Welding, and In-Shop Inspection," pp. 217–345, 2013.

[20] B. S. Austria, *Boehler Welding guide*, 09/2010 ed. Böhler Schweißtechnik Austria GmbH, 2010.

[21] Böhler, *Schweisszusätze für thermische Kraftwerke*. Böhler welding, 2010.

[22] and D. W. D. Dobeneck v., K. H. Steigerwald, S. G., B. R., D. Powers, O. K. Nazarenko, W. A. Dietrich, H. Irie, *An International History of Electron Beam Welding*. 2007.

[23] S. S. SST, "Geschichte der EB-Technik," 2014. [Online]. Available: http://www.steigerwald-eb.de/de/eb-technik/geschichte-der-eb-technik.html.

[24] D. Dobeneck, *Elektronenstrahlschweißen - Anwendungsbeispiele aus 30 Jahren Lohnschweißpraxis*, 2. Auflage. 2007.

[25] and S. J. U. Reisgen, S. Olschok, "A comparison of electron beam welding with laser beam welding in vacuum," in *International Electron Beam Welding Conference*, 2012, pp. 119–127.

[26] K. R. Schulze, "Immer dasselbe und doch jedes Mal anders," in *DVS Schweißen und Schneiden*, Vol. 7., 2011, pp. 392–397.

[27] V. Adam, U. Clauß, D. Dobeneck, T. Krüssel, and T. Löwer, "Electron beam welding - The fundamentals of a fascinating technology." Germany: pro-beam AG & Co. KGaA, 2011.

[28] H. Schultz, *Elektronenstrahlschweißen*, 2nd ed. Düsseldorf, 2000.

[29] Z. Sun and R. Karppi, "The application of electron beam welding for the joining of dissimilar metals: an overview," *J. Mater. Process. Technol.*, vol. 59, no. 3, pp. 257–267, May 1996.

[30] ISO 15609-1, "Anforderung und Qualifizierung von schweißverfahren für metallische Werkstoffe - Schweißanweisung - Teil 1: Lichtbogenschweißen." .

[31] DIN EN ISO 15614-11, "Anforderung und Qualifizierung von Schweißverfahren für metallische Werkstoffe - Schweißverfahrensprüfung, Teil 11: Elektronen- und Laserstrahlschweißen," 2002.

[32] DIN EN ISO 15614-1, "Anforderung und Qualifizierung von Schweißverfahren für metallische Werkstoffe - Schweißverfahrensprüfung, Teil 1: Lichtbogen- und Gasschweißen von Stählen und Lichtbogenschweißen von Nickel und Nickellegierungen," 2004.

[33] Fronius, "Magicwave 3000," *Fronius Oper. Man.*, 2013.

[34] DIN 50125, "Prüfung metallischer Werkstoffe - Zugproben." 2004.

[35] EN 10045-1, "Kerbschlagbiegeversuch nach Charpy - Prüfverfahren," 1990.

[36] ÖNORM EN 910, "Zerstörende Prüfung von Schweißnähten an metallischen Werkstoffen - Biegeprüfung," 1996.

[37] ÖNORM EN 1043-1, "Zerstörende Prüfung an Schweißnähten an metallischen Werkstoffen - Härteprüfung, Teil 1: Härteprüfung für Lichtbogenschweißverbindungen," 1996.

[38] ÖNORM EN 1321, "Zerstörende Prüfung von Schweißverbindungen an metallischen Werkstoffen - Makroskopische und mikroskopische Untersuchungen von Schweißnähten," 1996.

[39] K. Ernst, *Thermodynamische Berechnung der Phasengleichgewichte und der Ausscheidungskinetik in metallischen Werkstoffen*. TU-Graz, 1997.

[40] "http://matcalc.tuwien.ac.at." 2014.

[41] C. Ramskogler, "GA06911_Gefügecharakterisierung Nibas625," 2013.

[42] Y. Guo, B. Wang, and S. Hou, "Aging precipitation behavior and mechanical properties of Inconel 617 superalloy," *Acta Metall. Sin. (English Lett.*, vol. 26, no. 3, pp. 307–312, May 2013.

[43] TÜV Nord Systems GmbH & Co. KG, "Prüfbericht über die Durchführung einer Schweißverfahrensprüfung," 2013.

12 APPENDIX

TÜV Nord Systems GmbH & Co. KG
Zertifizierungsstelle für Druckgeräte
Region Magdeburg
Adelheidring 16, 39108 Magdeburg
Tel.: 0391/7366-0 • Fax: 0391/7366-333

TÜV NORD

Prüfbericht
(Inspection report)

über die Durchführung einer
(of a welding)

Schweißverfahrensprüfung
(production qualifikation test)

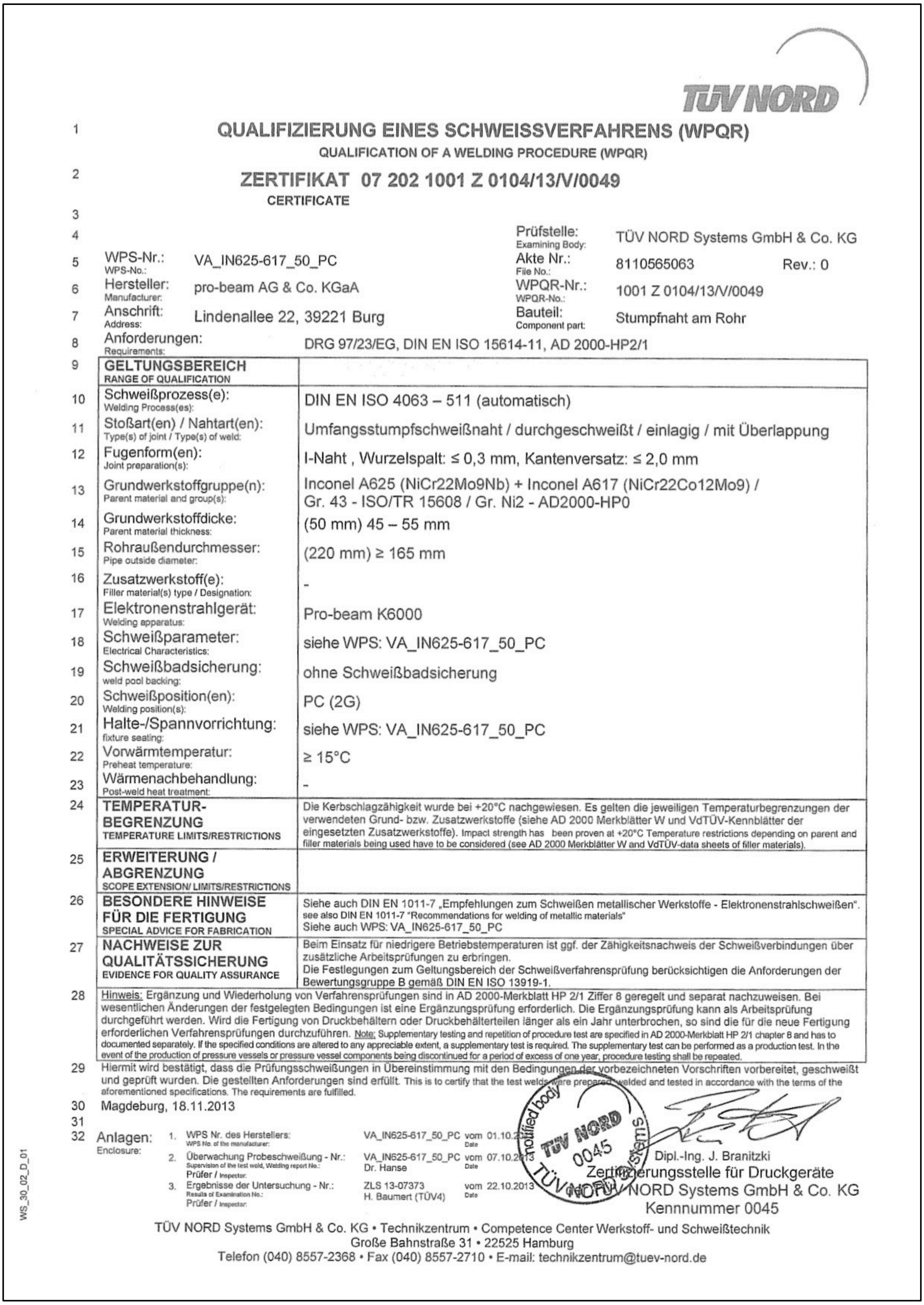
gemäß *(acc)* DGRL 97/23 EG, DIN EN ISO 15614-11

Auftraggeber: (customer)	**pro-beam AG & Co. KGaA** **Lindenallee 22** **39221 Burg**
Bezeichnung: (characteristic)	VP-0049-0104/13/V
Abmessungen: (Welding specimen)	Ø220 x 50 mm
Werkstoff: (material)	Inconel A625 (NiCr22Mo9Nb) + Inconel A617 (NiCr22Co12Mo9)
Schweißprozess: (welding process)	511 (Elektronenstrahlschweißen)
Schweißposition: (welding position)	PC
Nahtart: (type of seam)	BW

Zu diesem Bericht gehören:
(This report covers:)

2 Blatt *(page)* Zertifikat Nr. 07 202 1001 Z 0104/13/V/0049
2 Blatt *(page)* Prüfbericht *(report)* Überwachung der Probeschweißung *(Supervision of test welding)*
2 Blatt *(page)* Schweißanweisung (WPS-Nr. VA_IN625-617_50_PC)
5 Blatt *(pages)* Laborbericht ZLS (*Laboratory report*) - Nr. 13-07373
2 Blatt *(pages)* Durchstrahlungsprüfprotokoll (*radiographic test report*)- Nr. 76263/1-13
1 Blatt *(pages)* Protokoll PT-Prüfung (*Report of penetrant testing*) - Nr. 76263/3-13
1 Blatt *(pages)* Protokoll Sichtprüfung (*Report on visual examination*) - Nr. 76263/7-13

FIGURE 74: INSPECTION REPORT PRO-BEAM [43]



TÜV NORD

QUALIFIZIERUNG EINES SCHWEISSVERFAHRENS (WPQR)
QUALIFICATION OF A WELDING PROCEDURE (WPQR)

ZERTIFIKAT 07 202 1001 Z 0104/13/V/0049
CERTIFICATE

		Prüfstelle: Examining Body:	TÜV NORD Systems GmbH & Co. KG
WPS-Nr.: WPS-No.:	VA_IN625-617_50_PC	Akte Nr.: File No.:	8110565063 Rev.: 0
Hersteller: Manufacturer:	pro-beam AG & Co. KGaA	WPQR-Nr.: WPQR-No.:	1001 Z 0104/13/V/0049
Anschrift: Address:	Lindenallee 22, 39221 Burg	Bauteil: Component part:	Stumpfnaht am Rohr
Anforderungen: Requirements:	DRG 97/23/EG, DIN EN ISO 15614-11, AD 2000-HP2/1		

GELTUNGSBEREICH **RANGE OF QUALIFICATION**	
Schweißprozess(e): Welding Process(es):	DIN EN ISO 4063 – 511 (automatisch)
Stoßart(en) / Nahtart(en): Type(s) of joint / Type(s) of weld:	Umfangsstumpfschweißnaht / durchgeschweißt / einlagig / mit Überlappung
Fugenform(en): Joint preparation(s):	I-Naht , Wurzelspalt: ≤ 0,3 mm, Kantenversatz: ≤ 2,0 mm
Grundwerkstoffgruppe(n): Parent material and group(s):	Inconel A625 (NiCr22Mo9Nb) + Inconel A617 (NiCr22Co12Mo9) / Gr. 43 - ISO/TR 15608 / Gr. Ni2 - AD2000-HP0
Grundwerkstoffdicke: Parent material thickness:	(50 mm) 45 – 55 mm
Rohraußendurchmesser: Pipe outside diameter:	(220 mm) ≥ 165 mm
Zusatzwerkstoff(e): Filler material(s) type / Designation:	-
Elektronenstrahlgerät: Welding apparatus:	Pro-beam K6000
Schweißparameter: Electrical Characteristics:	siehe WPS: VA_IN625-617_50_PC
Schweißbadsicherung: weld pool backing:	ohne Schweißbadsicherung
Schweißposition(en): Welding position(s):	PC (2G)
Halte-/Spannvorrichtung: fixture seating:	siehe WPS: VA_IN625-617_50_PC
Vorwärmtemperatur: Preheat temperature:	≥ 15°C
Wärmenachbehandlung: Post-weld heat treatment:	-
TEMPERATUR-BEGRENZUNG **TEMPERATURE LIMITS/RESTRICTIONS**	Die Kerbschlagzähigkeit wurde bei +20°C nachgewiesen. Es gelten die jeweiligen Temperaturbegrenzungen der verwendeten Grund- bzw. Zusatzwerkstoffe (siehe AD 2000 Merkblätter W und VdTÜV-Kennblätter der eingesetzten Zusatzwerkstoffe). Impact strength has been proven at +20°C Temperature restrictions depending on parent and filler materials being used have to be considered (see AD 2000 Merkblätter W and VdTÜV-data sheets of filler materials).
ERWEITERUNG / ABGRENZUNG **SCOPE EXTENSION/ LIMITS/RESTRICTIONS**	
BESONDERE HINWEISE FÜR DIE FERTIGUNG **SPECIAL ADVICE FOR FABRICATION**	Siehe auch DIN EN 1011-7 „Empfehlungen zum Schweißen metallischer Werkstoffe - Elektronenstrahlschweißen". see also DIN EN 1011-7 "Recommendations for welding of metallic materials" Siehe auch WPS: VA_IN625-617_50_PC
NACHWEISE ZUR QUALITÄTSSICHERUNG **EVIDENCE FOR QUALITY ASSURANCE**	Beim Einsatz für niedrigere Betriebstemperaturen ist ggf. der Zähigkeitsnachweis der Schweißverbindungen über zusätzliche Arbeitsprüfungen zu erbringen. Die Festlegungen zum Geltungsbereich der Schweißverfahrensprüfung berücksichtigen die Anforderungen der Bewertungsgruppe B gemäß DIN EN ISO 13919-1.

Hinweis: Ergänzung und Wiederholung von Verfahrensprüfungen sind in AD 2000-Merkblatt HP 2/1 Ziffer 8 geregelt und separat nachzuweisen. Bei wesentlichen Änderungen der festgelegten Bedingungen ist eine Ergänzungsprüfung erforderlich. Die Ergänzungsprüfung kann als Arbeitsprüfung durchgeführt werden. Wird die Fertigung von Druckbehältern oder Druckbehälterteilen länger als ein Jahr unterbrochen, so sind die für die neue Fertigung erforderlichen Verfahrensprüfungen durchzuführen. Note: Supplementary testing and repetition of procedure test are specified in AD 2000-Merkblatt HP 2/1 chapter 8 and has to documented separately. If the specified conditions are altered to any appreciable extent, a supplementary test is required. The supplementary test can be performed as a production test. In the event of the production of pressure vessels or pressure vessel components being discontinued for a period of excess of one year, procedure testing shall be repeated.

Hiermit wird bestätigt, dass die Prüfungsschweißungen in Übereinstimmung mit den Bedingungen der vorbezeichneten Vorschriften vorbereitet, geschweißt und geprüft wurden. Die gestellten Anforderungen sind erfüllt. This is to certify that the test welds were prepared, welded and tested in accordance with the terms of the aforementioned specifications. The requirements are fulfilled.

Magdeburg, 18.11.2013

Anlagen:
Enclosure:

1. WPS Nr. des Herstellers: / WPS No. of the manufacturer: VA_IN625-617_50_PC vom / Date 01.10.2013
2. Überwachung Probeschweißung - Nr.: / Supervision of the test weld, Welding report No.: VA_IN625-617_50_PC vom / Date 07.10.2013; Prüfer / Inspector: Dr. Hanse
3. Ergebnisse der Untersuchung - Nr.: / Results of Examination No.: ZLS 13-07373 vom / Date 22.10.2013; Prüfer / Inspector: H. Baumert (TÜV4)

TÜV NORD 0045

Dipl.-Ing. J. Branitzki
Zertifizierungsstelle für Druckgeräte
TÜV NORD Systems GmbH & Co. KG
Kennnummer 0045

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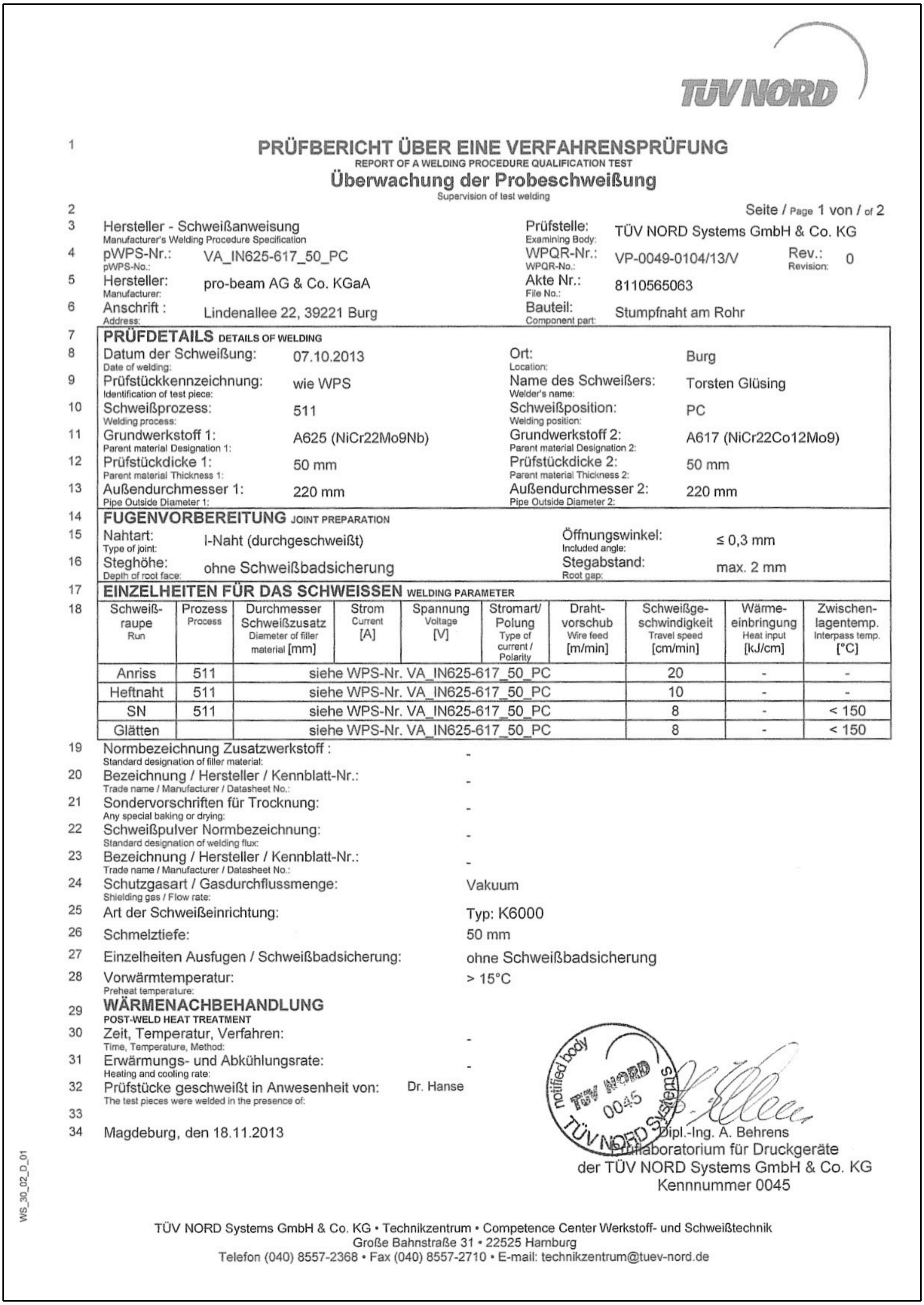
FIGURE 75: WPQR PRO-BEAM [43]



TÜV NORD

1 **PRÜFBERICHT ÜBER EINE VERFAHRENSPRÜFUNG**
REPORT OF A WELDING PROCEDURE QUALIFICATION TEST
Überwachung der Probeschweißung
Supervision of test welding

2 Seite / Page 1 von / of 2

3 Hersteller - Schweißanweisung (Manufacturer's Welding Procedure Specification) — Prüfstelle: (Examining Body:) TÜV NORD Systems GmbH & Co. KG

4 pWPS-Nr.: (pWPS-No.:) VA_IN625-617_50_PC — WPQR-Nr.: (WPQR-No.:) VP-0049-0104/13/V — Rev.: (Revision:) 0

5 Hersteller: (Manufacturer:) pro-beam AG & Co. KGaA — Akte Nr.: (File No.:) 8110565063

6 Anschrift : (Address:) Lindenallee 22, 39221 Burg — Bauteil: (Component part:) Stumpfnaht am Rohr

7 **PRÜFDETAILS** DETAILS OF WELDING

8 Datum der Schweißung: (Date of welding:) 07.10.2013 — Ort: (Location:) Burg

9 Prüfstückkennzeichnung: (Identification of test piece:) wie WPS — Name des Schweißers: (Welder's name:) Torsten Glüsing

10 Schweißprozess: (Welding process:) 511 — Schweißposition: (Welding position:) PC

11 Grundwerkstoff 1: (Parent material Designation 1:) A625 (NiCr22Mo9Nb) — Grundwerkstoff 2: (Parent material Designation 2:) A617 (NiCr22Co12Mo9)

12 Prüfstückdicke 1: (Parent material Thickness 1:) 50 mm — Prüfstückdicke 2: (Parent material Thickness 2:) 50 mm

13 Außendurchmesser 1: (Pipe Outside Diameter 1:) 220 mm — Außendurchmesser 2: (Pipe Outside Diameter 2:) 220 mm

14 **FUGENVORBEREITUNG** JOINT PREPARATION

15 Nahtart: (Type of joint:) I-Naht (durchgeschweißt) — Öffnungswinkel: (Included angle:) ≤ 0,3 mm

16 Steghöhe: (Depth of root face:) ohne Schweißbadsicherung — Stegabstand: (Root gap:) max. 2 mm

17 **EINZELHEITEN FÜR DAS SCHWEISSEN** WELDING PARAMETER

18

Schweiß-raupe Run	Prozess Process	Durchmesser Schweißzusatz Diameter of filler material [mm]	Strom Current [A]	Spannung Voltage [V]	Stromart/ Polung Type of current / Polarity	Draht-vorschub Wire feed [m/min]	Schweißge-schwindigkeit Travel speed [cm/min]	Wärme-einbringung Heat input [kJ/cm]	Zwischen-lagentemp. Interpass temp. [°C]
Anriss	511	siehe WPS-Nr. VA_IN625-617_50_PC					20	-	-
Heftnaht	511	siehe WPS-Nr. VA_IN625-617_50_PC					10	-	-
SN	511	siehe WPS-Nr. VA_IN625-617_50_PC					8	-	< 150
Glätten		siehe WPS-Nr. VA_IN625-617_50_PC					8	-	< 150

19 Normbezeichnung Zusatzwerkstoff : (Standard designation of filler material:) -

20 Bezeichnung / Hersteller / Kennblatt-Nr.: (Trade name / Manufacturer / Datasheet No.:) -

21 Sondervorschriften für Trocknung: (Any special baking or drying:) -

22 Schweißpulver Normbezeichnung: (Standard designation of welding flux:) -

23 Bezeichnung / Hersteller / Kennblatt-Nr.: (Trade name / Manufacturer / Datasheet No.:) -

24 Schutzgasart / Gasdurchflussmenge: (Shielding gas / Flow rate:) Vakuum

25 Art der Schweißeinrichtung: Typ: K6000

26 Schmelztiefe: 50 mm

27 Einzelheiten Ausfugen / Schweißbadsicherung: ohne Schweißbadsicherung

28 Vorwärmtemperatur: (Preheat temperature:) > 15°C

29 **WÄRMENACHBEHANDLUNG**
POST-WELD HEAT TREATMENT

30 Zeit, Temperatur, Verfahren: (Time, Temperature, Method:) -

31 Erwärmungs- und Abkühlungsrate: (Heating and cooling rate:) -

32 Prüfstücke geschweißt in Anwesenheit von: (The test pieces were welded in the presence of:) Dr. Hanse

33

34 Magdeburg, den 18.11.2013

0045

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der TÜV NORD Systems GmbH & Co. KG
Kennnummer 0045

WS_30_02_D_01

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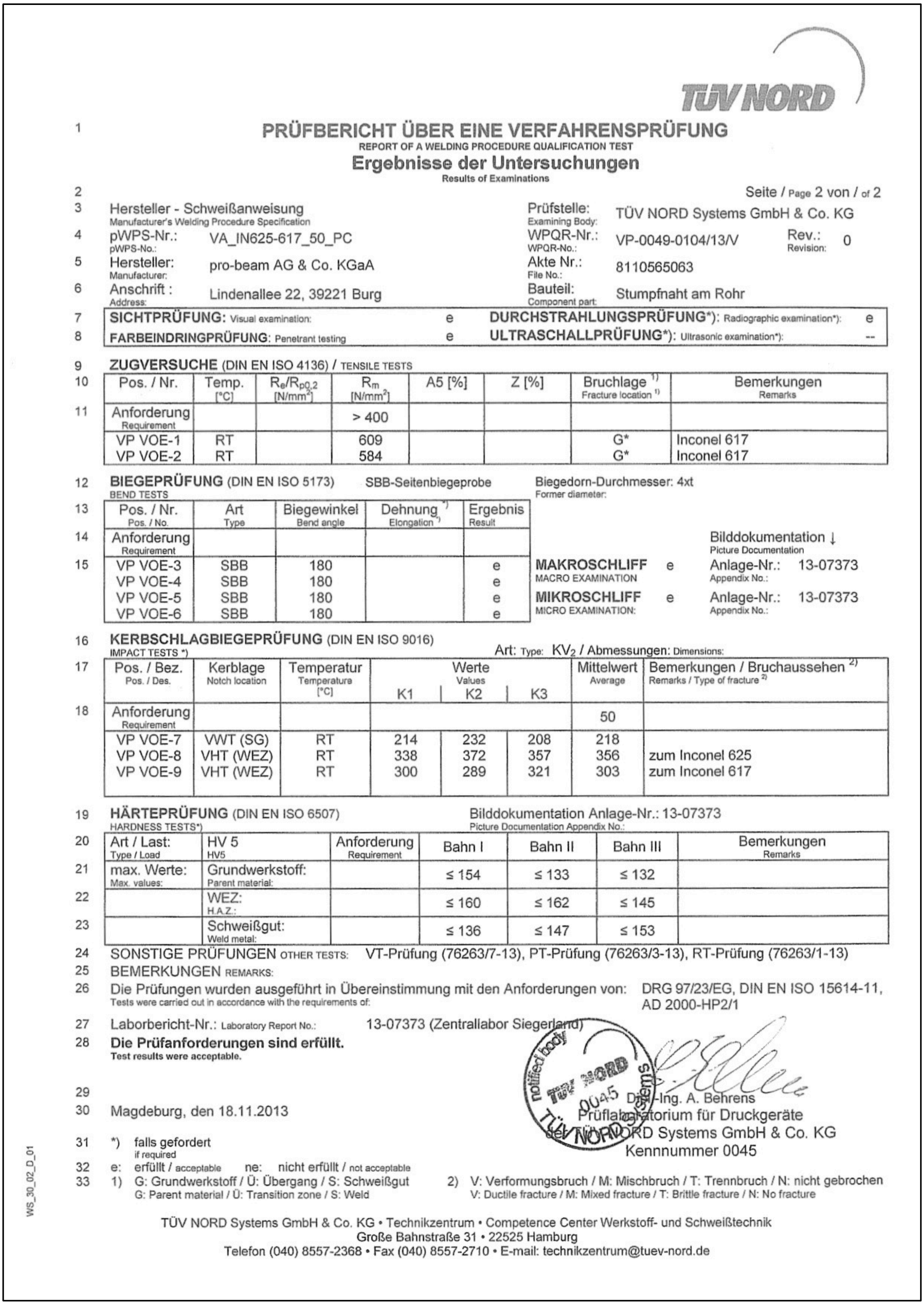
FIGURE 76: WPQT PRO-BEAM PAGE 1/2 [43]



TÜV NORD

PRÜFBERICHT ÜBER EINE VERFAHRENSPRÜFUNG
REPORT OF A WELDING PROCEDURE QUALIFICATION TEST

Ergebnisse der Untersuchungen
Results of Examinations

Seite / Page 2 von / of 2

Hersteller - Schweißanweisung Manufacturer's Welding Procedure Specification		Prüfstelle: Examining Body:	TÜV NORD Systems GmbH & Co. KG
pWPS-Nr.: pWPS-No.:	VA_IN625-617_50_PC	WPQR-Nr.: WPQR-No.:	VP-0049-0104/13/V Rev.: Revision: 0
Hersteller: Manufacturer:	pro-beam AG & Co. KGaA	Akte Nr.: File No.:	8110565063
Anschrift : Address:	Lindenallee 22, 39221 Burg	Bauteil: Component part:	Stumpfnaht am Rohr

SICHTPRÜFUNG: Visual examination:	e	**DURCHSTRAHLUNGSPRÜFUNG*):** Radiographic examination*):	e
FARBEINDRINGPRÜFUNG: Penetrant testing	e	**ULTRASCHALLPRÜFUNG*):** Ultrasonic examination*):	--

ZUGVERSUCHE (DIN EN ISO 4136) / TENSILE TESTS

Pos. / Nr.	Temp. [°C]	$R_e/R_{p0,2}$ [N/mm²]	R_m [N/mm²]	A5 [%]	Z [%]	Bruchlage 1) Fracture location 1)	Bemerkungen Remarks
Anforderung Requirement			> 400				
VP VOE-1	RT		609			G*	Inconel 617
VP VOE-2	RT		584			G*	Inconel 617

BIEGEPRÜFUNG (DIN EN ISO 5173) SBB-Seitenbiegeprobe Biegedorn-Durchmesser: 4xt
BEND TESTS Former diameter:

Pos. / Nr. Pos. / No.	Art Type	Biegewinkel Bend angle	Dehnung *) Elongation *)	Ergebnis Result
Anforderung Requirement				
VP VOE-3	SBB	180		e
VP VOE-4	SBB	180		e
VP VOE-5	SBB	180		e
VP VOE-6	SBB	180		e

Bilddokumentation ↓
Picture Documentation

MAKROSCHLIFF MACRO EXAMINATION	e	Anlage-Nr.: Appendix No.:	13-07373
MIKROSCHLIFF MICRO EXAMINATION:	e	Anlage-Nr.: Appendix No.:	13-07373

KERBSCHLAGBIEGEPRÜFUNG (DIN EN ISO 9016)
IMPACT TESTS *) Art: Type: KV_2 / Abmessungen: Dimensions:

Pos. / Bez. Pos. / Des.	Kerblage Notch location	Temperatur Temperature [°C]	Werte Values K1	 K2	 K3	Mittelwert Average	Bemerkungen / Bruchaussehen 2) Remarks / Type of fracture 2)
Anforderung Requirement						50	
VP VOE-7	VWT (SG)	RT	214	232	208	218	
VP VOE-8	VHT (WEZ)	RT	338	372	357	356	zum Inconel 625
VP VOE-9	VHT (WEZ)	RT	300	289	321	303	zum Inconel 617

HÄRTEPRÜFUNG (DIN EN ISO 6507) Bilddokumentation Anlage-Nr.: 13-07373
HARDNESS TESTS*) Picture Documentation Appendix No.:

Art / Last: Type / Load	HV 5 HV5	Anforderung Requirement	Bahn I	Bahn II	Bahn III	Bemerkungen Remarks
max. Werte: Max. values:	Grundwerkstoff: Parent material:		≤ 154	≤ 133	≤ 132	
	WEZ: H.A.Z.:		≤ 160	≤ 162	≤ 145	
	Schweißgut: Weld metal:		≤ 136	≤ 147	≤ 153	

SONSTIGE PRÜFUNGEN OTHER TESTS: VT-Prüfung (76263/7-13), PT-Prüfung (76263/3-13), RT-Prüfung (76263/1-13)

BEMERKUNGEN REMARKS:

Die Prüfungen wurden ausgeführt in Übereinstimmung mit den Anforderungen von: DRG 97/23/EG, DIN EN ISO 15614-11, AD 2000-HP2/1
Tests were carried out in accordance with the requirements of:

Laborbericht-Nr.: Laboratory Report No.: 13-07373 (Zentrallabor Siegerland)

Die Prüfanforderungen sind erfüllt.
Test results were acceptable.

Magdeburg, den 18.11.2013

0045

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der TÜV NORD Systems GmbH & Co. KG
Kennnummer 0045

*) falls gefordert
if required

e: erfüllt / acceptable ne: nicht erfüllt / not acceptable

1) G: Grundwerkstoff / Ü: Übergang / S: Schweißgut
G: Parent material / Ü: Transition zone / S: Weld

2) V: Verformungsbruch / M: Mischbruch / T: Trennbruch / N: nicht gebrochen
V: Ductile fracture / M: Mixed fracture / T: Brittle fracture / N: No fracture

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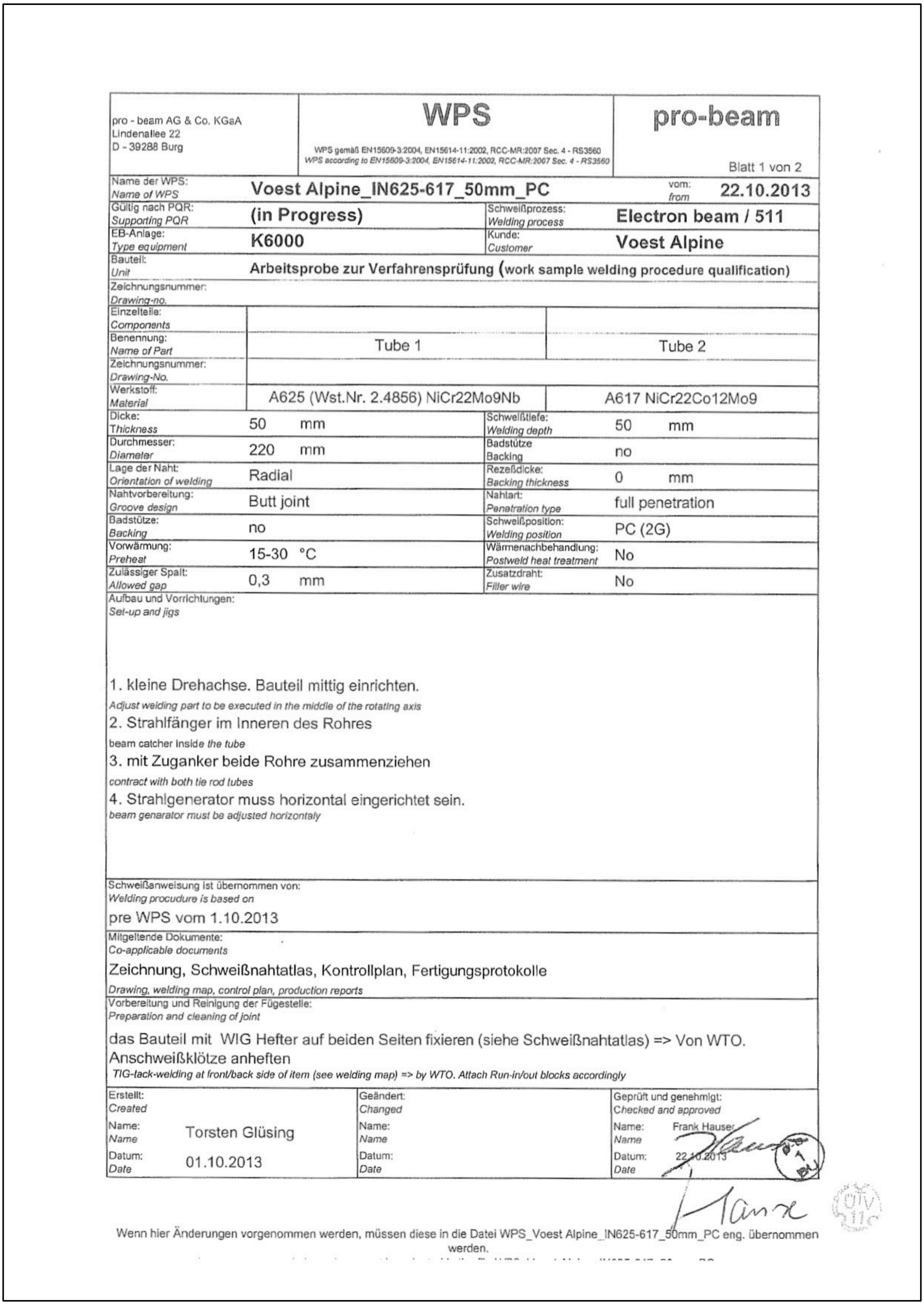
FIGURE 77: WPQT PRO-BEAM PAGE 2/2 [43]



pro - beam AG & Co. KGaA
Lindenallee 22
D - 39288 Burg

WPS

WPS gemäß EN15609-3:2004, EN15614-11:2002, RCC-MR:2007 Sec. 4 - RS3560
WPS according to EN15609-3:2004, EN15614-11:2002, RCC-MR:2007 Sec. 4 - RS3560

pro-beam

Blatt 1 von 2

Name der WPS: *Name of WPS*	**Voest Alpine_IN625-617_50mm_PC**	vom: *from*	**22.10.2013**
Gültig nach PQR: *Supporting PQR*	**(in Progress)**	Schweißprozess: *Welding process*	**Electron beam / 511**
EB-Anlage: *Type equipment*	**K6000**	Kunde: *Customer*	**Voest Alpine**
Bauteil: *Unit*	**Arbeitsprobe zur Verfahrensprüfung (work sample welding procedure qualification)**		
Zeichnungsnummer: *Drawing-no.*			

Einzelteile: *Components*		
Benennung: *Name of Part*	Tube 1	Tube 2
Zeichnungsnummer: *Drawing-No.*		
Werkstoff: *Material*	A625 (Wst.Nr. 2.4856) NiCr22Mo9Nb	A617 NiCr22Co12Mo9

Dicke: *Thickness*	50 mm	Schweißtiefe: *Welding depth*	50 mm
Durchmesser: *Diameter*	220 mm	Badstütze *Backing*	no
Lage der Naht: *Orientation of welding*	Radial	Rezeßdicke: *Backing thickness*	0 mm
Nahtvorbereitung: *Groove design*	Butt joint	Nahtart: *Penetration type*	full penetration
Badstütze: *Backing*	no	Schweißposition: *Welding position*	PC (2G)
Vorwärmung: *Preheat*	15-30 °C	Wärmenachbehandlung: *Postweld heat treatment*	No
Zulässiger Spalt: *Allowed gap*	0,3 mm	Zusatzdraht: *Filler wire*	No

Aufbau und Vorrichtungen:
Set-up and jigs

1. kleine Drehachse. Bauteil mittig einrichten.
Adjust welding part to be executed in the middle of the rotating axis
2. Strahlfänger im Inneren des Rohres
beam catcher inside *the tube*
3. mit Zuganker beide Rohre zusammenziehen
contract with both tie rod tubes
4. Strahlgenerator muss horizontal eingerichtet sein.
beam genarator must be adjusted horizontaly

Schweißanweisung ist übernommen von:
Welding procudure is based on

pre WPS vom 1.10.2013

Mitgeltende Dokumente:
Co-applicable documents

Zeichnung, Schweißnahtatlas, Kontrollplan, Fertigungsprotokolle
Drawing, welding map, control plan, production reports

Vorbereitung und Reinigung der Fügestelle:
Preparation and cleaning of joint

das Bauteil mit WIG Hefter auf beiden Seiten fixieren (siehe Schweißnahtatlas) => Von WTO. Anschweißklötze anheften
TIG-tack-welding at front/back side of item (see welding map) => by WTO. Attach Run-in/out blocks accordingly

Erstellt: *Created*		Geändert: *Changed*		Geprüft und genehmigt: *Checked and approved*	
Name: *Name*	Torsten Glüsing	Name: *Name*		Name: *Name*	Frank Hauser
Datum: *Date*	01.10.2013	Datum: *Date*		Datum: *Date*	22.10.2013

Wenn hier Änderungen vorgenommen werden, müssen diese in die Datei WPS_Voest Alpine_IN625-617_50mm_PC eng. übernommen werden.

FIGURE 78: PWPS PRO-BEAM PAGE 1/2 [43]

pro - beam AG & Co. KGaA
Lindenallee 22
D - 39288 Burg

WPS

WPS gemäß EN15609-3:2004, EN15614-11:2002, RCC-MR:2007 Sec. 4 - RS3560
WPS according to EN15609-3:2004, EN15614-11:2002, RCC-MR:2007 Sec. 4 - RS3560

pro-beam

Blatt 2 von 2

Name der WPS: *Name of WPS*	**Voest Alpine_IN625-617_50mm_PC**	vom: *from*	**22.10.2013**
Gültig nach PQR: *Supporting PQR*	**(in Progress)**	Schweißprozess: *Welding process*	**Electron beam / 511**
EB-Anlage: *Type equipment*	**K6000**	Kunde: *Customer*	**Voest Alpine**
Bauteil: *Unit*	**Arbeitsprobe zur Verfahrensprüfung (work sample welding procedure qualification)**		
Zeichnungsnummer: *Drawing-no.*			

Prüfungen und Maßnahmen vor dem Schweißen:
Approvals and actions before welding

Vor Fertigungsbeginn eine Arbeitsprobe schweißen und Kontrollschliff anfertigen. Spaltmaß und Kantenversatz messen, protokollieren und bei Freigabe fortfahren.

Fokus bei 20mA immer auf Bauteil (Spalt) bestimmen und ins Programm eingeben!!!

Trial weld and cross section before production, measurement of gap and misalignment, fill-out the reports, continue after approval. Determine the lens current with 20mA on the items gap and adopt in program!!!

Schweißparameter
Welding parameters

Beschleunigungsspannung: *Acceleration voltage*	80	kV	Linsenstrom auf Oberfläche: *Focusing lens current on surface*	2140	mA
Strahlerzeugertyp / System: *EB generator system*	80-40-1		Strahlstrom bei Linsenstrom Bestimmung: *Beam current for finding lens current*	20	mA
Kathode: *Cathode*	St'wald 35-95 (70µm)		Höhe über Tisch *level from the ground*	500	mm
Außerhalb Drehachse: *Welding Position out of rotation axis*	-	mm	Kalibrierwert für Strahlablenkung: *Calibration value for beam deflection*	12600	
Arbeitsdruck Strahlerzeuger: *Work pressure gun*	≤ 10-4	mbar	Arbeitsdruck Kammer: *Work pressure chamber*	≤ 3*10-3	mbar
Strahl gepulst oder cw: *Beam pulse or cw*	cw		Strahlknick: *Angle of beam axis*	-	mA
Pulsen Frequenz *Pulse frequency*	-	Hz	Pulsen Tastverhältnis: *Pulse duty cycle*	-	%

	Strahl-strom	Linsen-strom	Schweiß-geschw.	Umlauf-zeit	Strahloszillation			Slope		Strahl-leistung	Sonstiges
					Form/Lage	Frequenz	Breite	ein	aus		
	Beam current	*Lens current*	*Welding speed*	*Weld time*	*Oscillation/ direction*	*Oscillation frequency*	*Oscillation width*	*Slope up*	*Slope down*	*Beam Power*	*Various*
	mA	mA	mm/s	min	-	Hz	mm	mm	mm	kW	
Anriss *Witness line*	3	±0	20	-	Spot	-	-	40	80	0,24	
Heftnaht *Tack weld*	40	±0	10	-	Kreis	817	X=0,8 Y=0,8	40	80	3,2	SQ_Heft (1,1,1,2)
Schweißnaht *Weld*	260	-80	8	-	Parabel $\langle \rightarrow$	817	X=1,0 Y=2,0	40	80	20,8	_Slout +10mA
Kosmetik *Wash Pass*	70	+ 50	8	-	Parabel $\langle \rightarrow$	817	X=1,5 Y=2,5	40	80	5,6	

CNC-Programm:
NC-program

VoestAlpine_WPD\AG_220_PC_C.MPF

Prüfungen und Maßnahmen beim Schweißen:
Approvals and actions during welding

Positionieren - Anriss - Heften , dann Schweißen mit ELO ONLINE (Nachführung per Hand möglich)
Positioning - scan - witness line - tack-welding and weld with ELO ONLINE (manual tracking allowed)

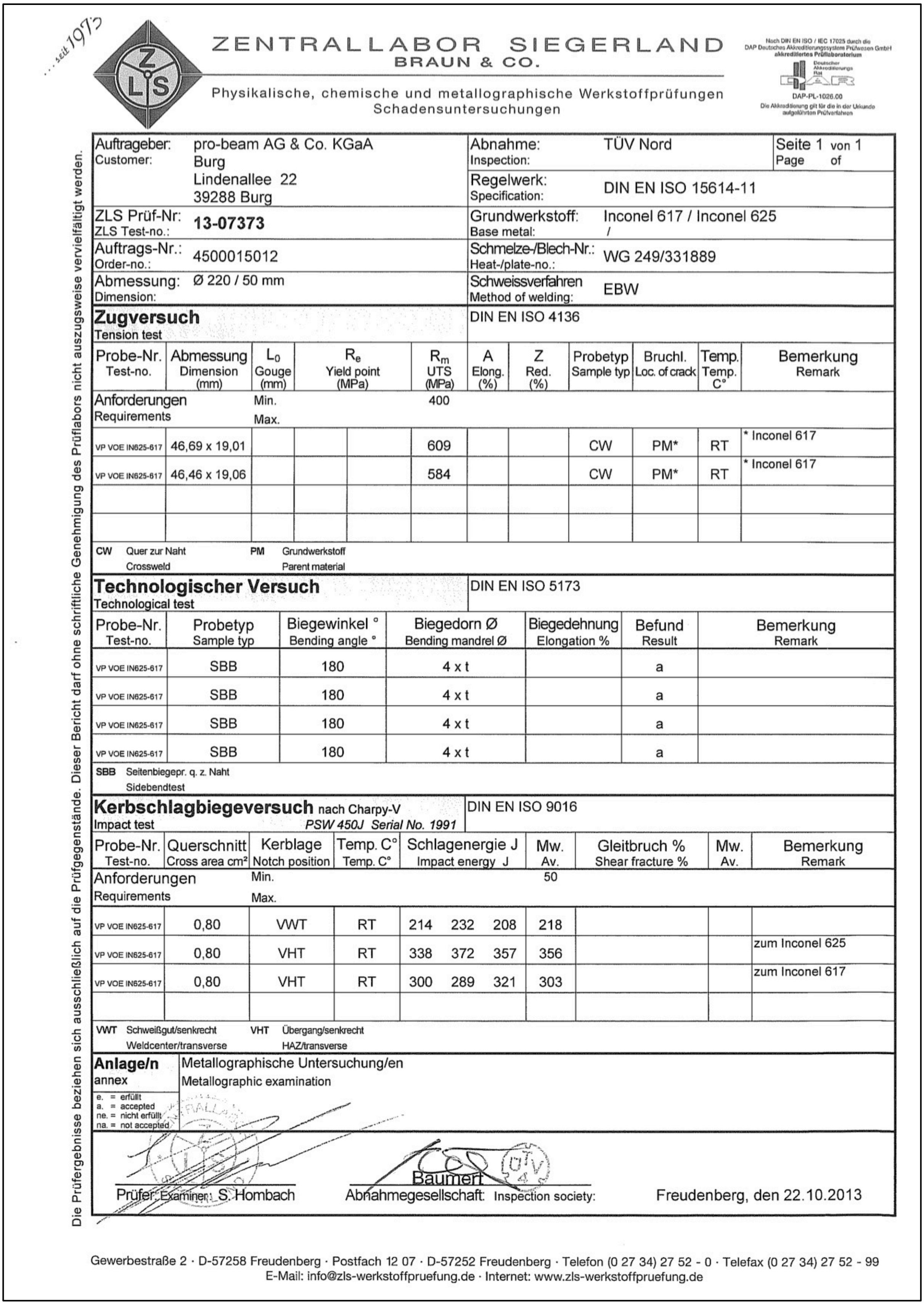
Prüfungen und Maßnahmen nach dem Schweißen:
Approvals and actions after welding

alle losen Schweißspritzer entfernen
removal of all loosespatter

Sichtprüfung, RT, PT, Ermittlung der mech. technol. Kennwerte bei ZLS
Visual test, RT, PT, determination of the mech. technol. Characteristics by ZLS

Wenn hier Änderungen vorgenommen werden, müssen diese in die Datei WPS_Voest Alpine_IN625-617_50mm_PC eng. übernommen werden.

FIGURE 79: PWPS PRO-BEAM PAGE 2/2 [43]



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Physikalische, chemische und metallographische Werkstoffprüfungen
Schadensuntersuchungen

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Deutscher Akkreditierungs Rat
DAP-PL-1026.00
Die Akkreditierung gilt für die in der Urkunde aufgeführten Prüfverfahren

Auftrageber: Customer:	pro-beam AG & Co. KGaA Burg Lindenallee 22 39288 Burg	Abnahme: Inspection:	TÜV Nord
		Seite 1 von 1 Page of	
		Regelwerk: Specification:	DIN EN ISO 15614-11
ZLS Prüf-Nr: ZLS Test-no.:	**13-07373**	Grundwerkstoff: Base metal:	Inconel 617 / Inconel 625 /
Auftrags-Nr.: Order-no.:	4500015012	Schmelze-/Blech-Nr.: Heat-/plate-no.:	WG 249/331889
Abmessung: Dimension:	Ø 220 / 50 mm	Schweissverfahren Method of welding:	EBW

Zugversuch
Tension test

DIN EN ISO 4136

Probe-Nr. Test-no.	Abmessung Dimension (mm)	L_0 Gouge (mm)	R_e Yield point (MPa)	R_m UTS (MPa)	A Elong. (%)	Z Red. (%)	Probetyp Sample typ	Bruchl. Loc. of crack	Temp. Temp. C°	Bemerkung Remark
Anforderungen Requirements		Min. Max.		400						
VP VOE IN625-617	46,69 x 19,01			609			CW	PM*	RT	* Inconel 617
VP VOE IN625-617	46,46 x 19,06			584			CW	PM*	RT	* Inconel 617

CW Quer zur Naht / Crossweld **PM** Grundwerkstoff / Parent material

Technologischer Versuch
Technological test

DIN EN ISO 5173

Probe-Nr. Test-no.	Probetyp Sample typ	Biegewinkel ° Bending angle °	Biegedorn Ø Bending mandrel Ø	Biegedehnung Elongation %	Befund Result	Bemerkung Remark
VP VOE IN625-617	SBB	180	4 x t		a	
VP VOE IN625-617	SBB	180	4 x t		a	
VP VOE IN625-617	SBB	180	4 x t		a	
VP VOE IN625-617	SBB	180	4 x t		a	

SBB Seitenbiegepr. q. z. Naht / Sidebendtest

Kerbschlagbiegeversuch nach Charpy-V
Impact test *PSW 450J Serial No. 1991*

DIN EN ISO 9016

Probe-Nr. Test-no.	Querschnitt Cross area cm²	Kerblage Notch position	Temp. C° Temp. C°	Schlagenergie J Impact energy J			Mw. Av.	Gleitbruch % Shear fracture %	Mw. Av.	Bemerkung Remark
Anforderungen Requirements		Min. Max.					50			
VP VOE IN625-617	0,80	VWT	RT	214	232	208	218			
VP VOE IN625-617	0,80	VHT	RT	338	372	357	356			zum Inconel 625
VP VOE IN625-617	0,80	VHT	RT	300	289	321	303			zum Inconel 617

VWT Schweißgut/senkrecht / Weldcenter/transverse **VHT** Übergang/senkrecht / HAZ/transverse

Anlage/n
annex

Metallographische Untersuchung/en
Metallographic examination

e. = erfüllt
a. = accepted
ne. = nicht erfüllt
na. = not accepted

Prüfer: Examiner: S. Hombach

Baumert
Abnahmegesellschaft: Inspection society:

Freudenberg, den 22.10.2013

Die Prüfergebnisse beziehen sich ausschließlich auf die Prüfgegenstände. Dieser Bericht darf ohne schriftliche Genehmigung des Prüflabors nicht auszugsweise vervielfältigt werden.

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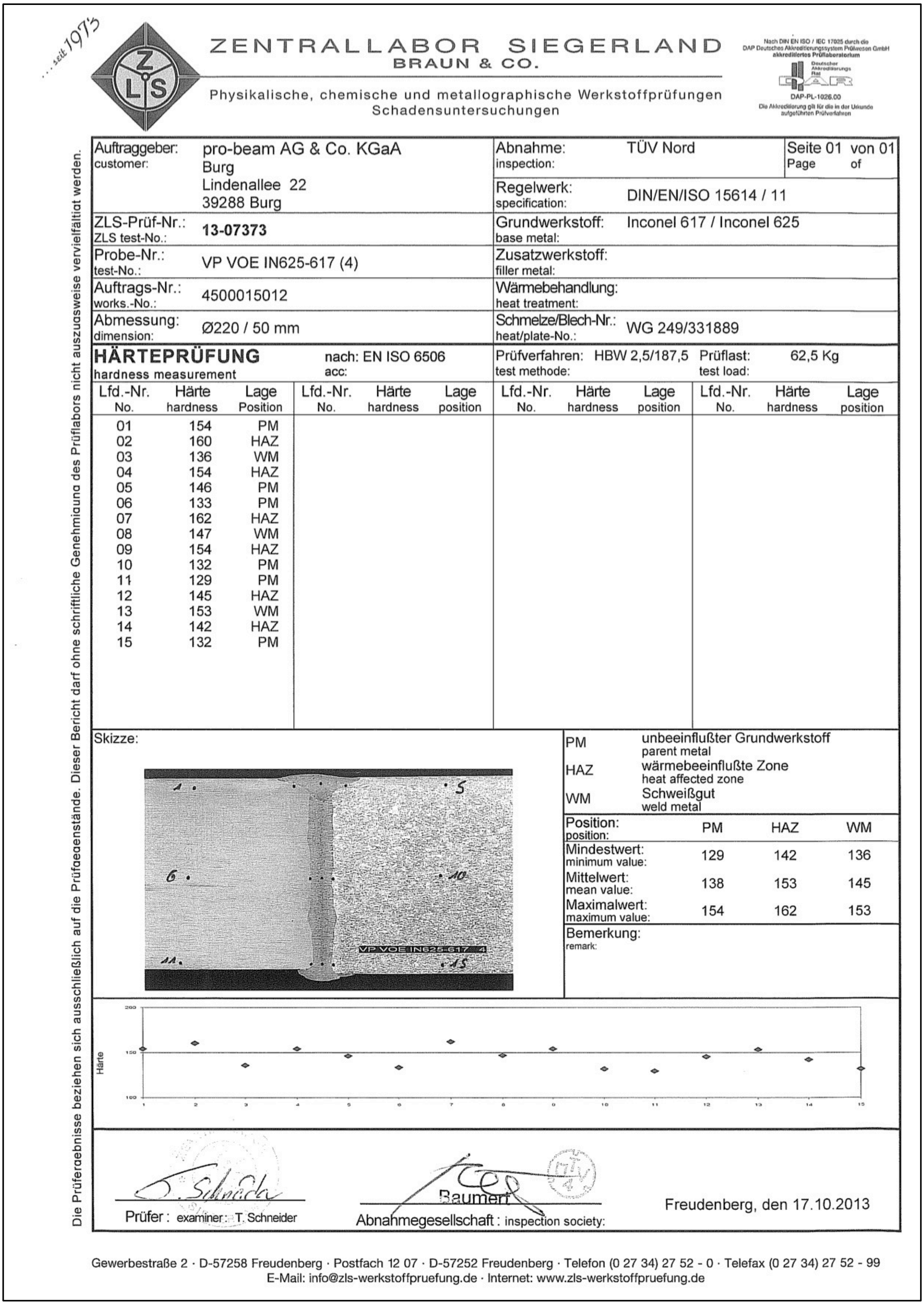
E-Mail: info@zls-werkstoffpruefung.de · Internet: www.zls-werkstoffpruefung.de

FIGURE 80: TENSILE TEST PRO-BEAM [43]



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Physikalische, chemische und metallographische Werkstoffprüfungen
Schadensuntersuchungen

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Deutscher Akkreditierungs Rat
DAR
DAP-PL-1026.00
Die Akkreditierung gilt für die in der Urkunde aufgeführten Prüfverfahren

Auftraggeber: customer:	pro-beam AG & Co. KGaA Burg Lindenallee 22 39288 Burg	Abnahme: inspection:	TÜV Nord	Seite 01 von 01 Page of	
		Regelwerk: specification:	DIN/EN/ISO 15614 / 11		
ZLS-Prüf-Nr.: ZLS test-No.:	**13-07373**	Grundwerkstoff: base metal:	Inconel 617 / Inconel 625		
Probe-Nr.: test-No.:	VP VOE IN625-617 (4)	Zusatzwerkstoff: filler metal:			
Auftrags-Nr.: works.-No.:	4500015012	Wärmebehandlung: heat treatment:			
Abmessung: dimension:	Ø220 / 50 mm	Schmelze/Blech-Nr.: heat/plate-No.:	WG 249/331889		
HÄRTEPRÜFUNG hardness measurement	nach: EN ISO 6506 acc:	Prüfverfahren: test methode:	HBW 2,5/187,5	Prüflast: test load:	62,5 Kg

Lfd.-Nr. No.	Härte hardness	Lage Position	Lfd.-Nr. No.	Härte hardness	Lage position	Lfd.-Nr. No.	Härte hardness	Lage position	Lfd.-Nr. No.	Härte hardness	Lage position
01	154	PM									
02	160	HAZ									
03	136	WM									
04	154	HAZ									
05	146	PM									
06	133	PM									
07	162	HAZ									
08	147	WM									
09	154	HAZ									
10	132	PM									
11	129	PM									
12	145	HAZ									
13	153	WM									
14	142	HAZ									
15	132	PM									

Skizze:

PM	unbeeinflußter Grundwerkstoff parent metal	
HAZ	wärmebeeinflußte Zone heat affected zone	
WM	Schweißgut weld metal	

Position: position:	PM	HAZ	WM
Mindestwert: minimum value:	129	142	136
Mittelwert: mean value:	138	153	145
Maximalwert: maximum value:	154	162	153

Bemerkung:
remark:

T. Schneider
Prüfer : examiner : T. Schneider

Baumert
Abnahmegesellschaft : inspection society:

Freudenberg, den 17.10.2013

Die Prüfergebnisse beziehen sich ausschließlich auf die Prüfgegenstände. Dieser Bericht darf ohne schriftliche Genehmigung des Prüflabors nicht auszugsweise vervielfältigt werden.

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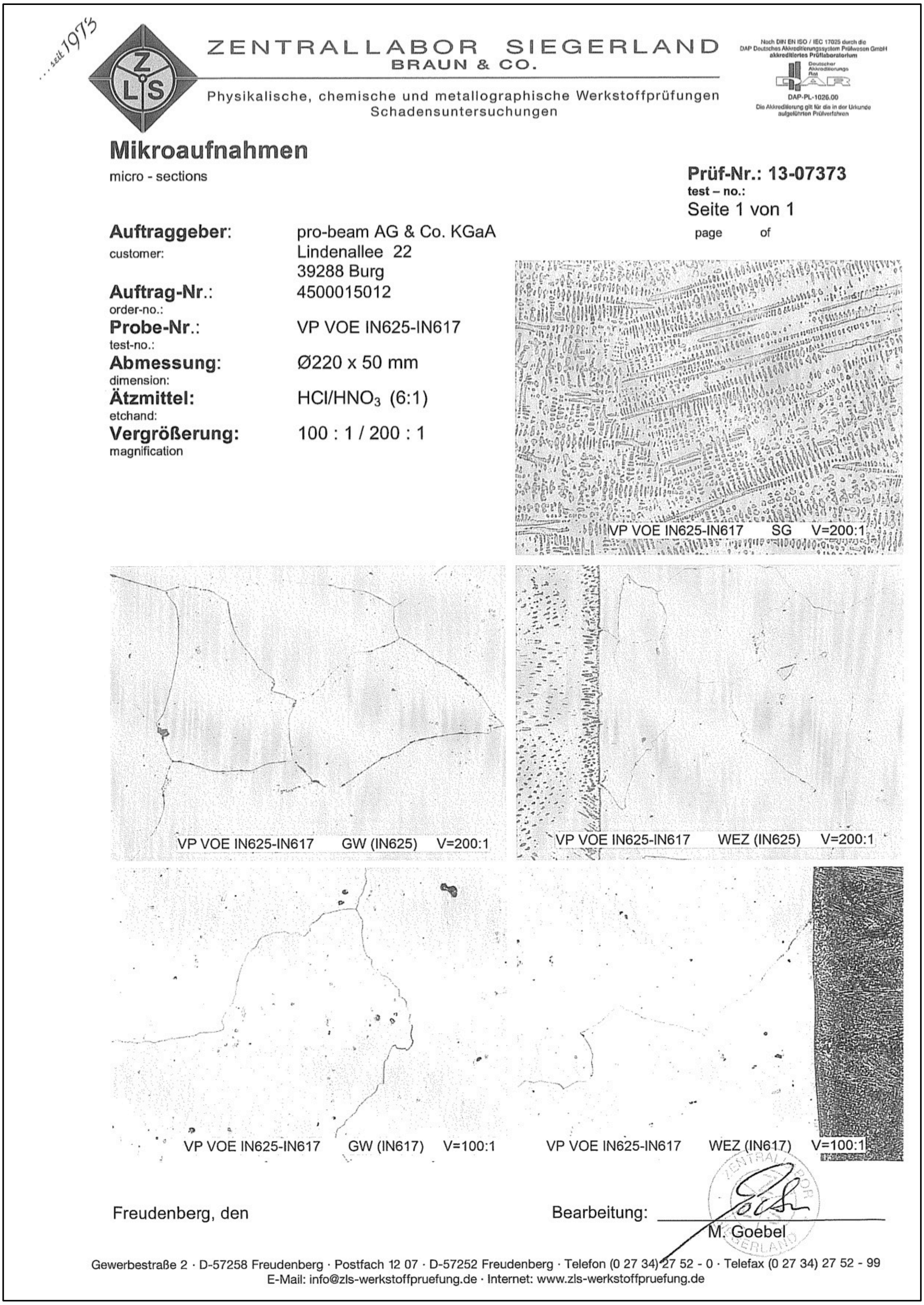
FIGURE 81: HARDNESS TEST PRO-BEAM [43]



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Mikroaufnahmen
micro - sections

Prüf-Nr.: 13-07373
test – no.:
Seite 1 von 1
page of

Auftraggeber: pro-beam AG & Co. KGaA
customer: Lindenallee 22
39288 Burg
Auftrag-Nr.: 4500015012
order-no.:
Probe-Nr.: VP VOE IN625-IN617
test-no.:
Abmessung: Ø220 x 50 mm
dimension:
Ätzmittel: HCl/HNO_3 (6:1)
etchand:
Vergrößerung: 100 : 1 / 200 : 1
magnification

VP VOE IN625-IN617 SG V=200:1

VP VOE IN625-IN617 GW (IN625) V=200:1

VP VOE IN625-IN617 WEZ (IN625) V=200:1

VP VOE IN625-IN617 GW (IN617) V=100:1

VP VOE IN625-IN617 WEZ (IN617) V=100:1

Freudenberg, den

Bearbeitung:
M. Goebel

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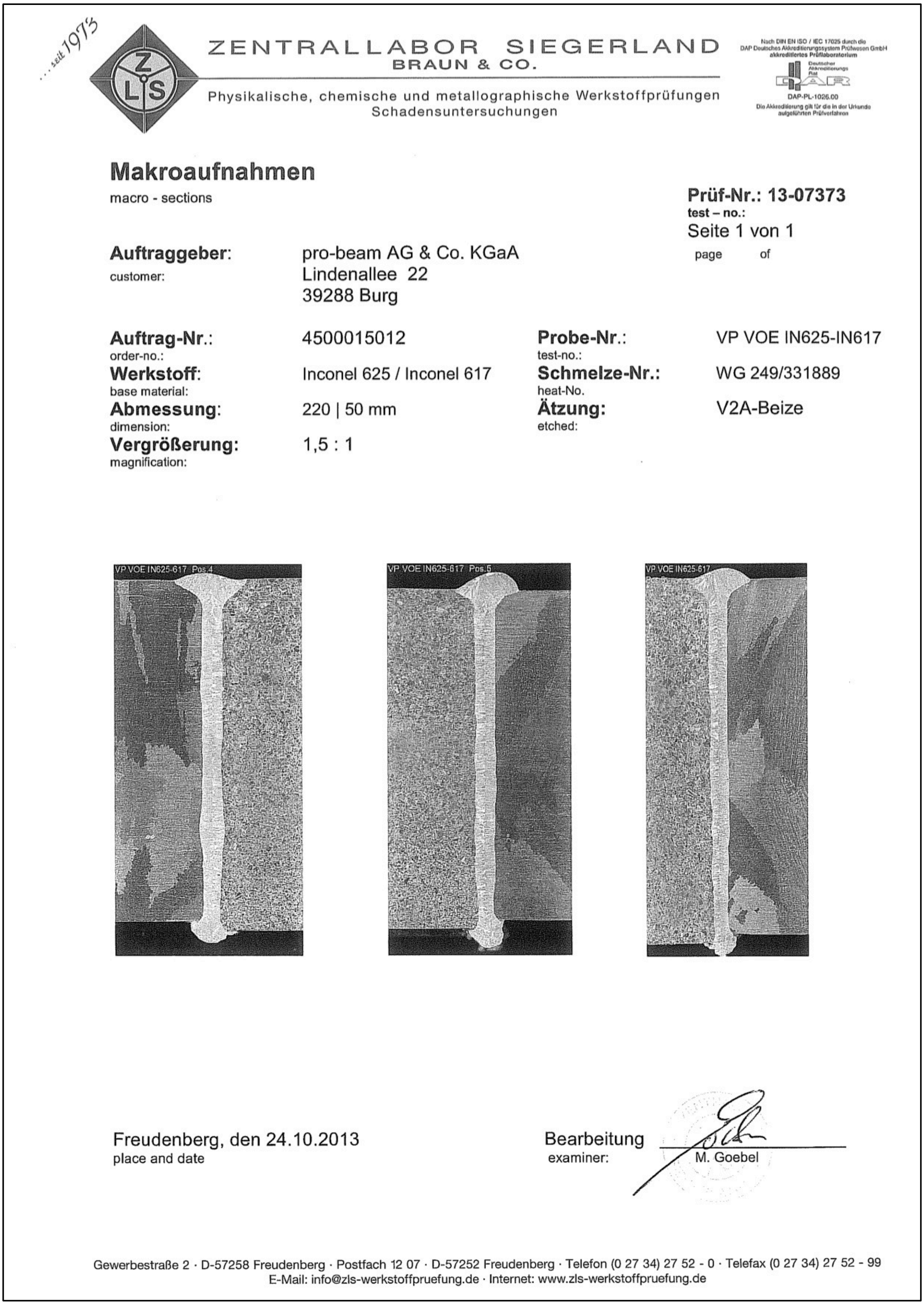
FIGURE 82: MICROSCOPY PRO-BEAM [43]



... seit 1973

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Physikalische, chemische und metallographische Werkstoffprüfungen
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DAP-PL-1026.00
Die Akkreditierung gilt für die in der Urkunde aufgeführten Prüfverfahren

Makroaufnahmen
macro - sections

Prüf-Nr.: 13-07373
test – no.:
Seite 1 von 1
page of

Auftraggeber: pro-beam AG & Co. KGaA
customer:
Lindenallee 22
39288 Burg

Auftrag-Nr.: 4500015012
order-no.:
Probe-Nr.: VP VOE IN625-IN617
test-no.:
Werkstoff: Inconel 625 / Inconel 617
base material:
Schmelze-Nr.: WG 249/331889
heat-No.
Abmessung: 220 | 50 mm
dimension:
Ätzung: V2A-Beize
etched:
Vergrößerung: 1,5 : 1
magnification:

Freudenberg, den 24.10.2013
place and date

Bearbeitung
examiner:
M. Goebel

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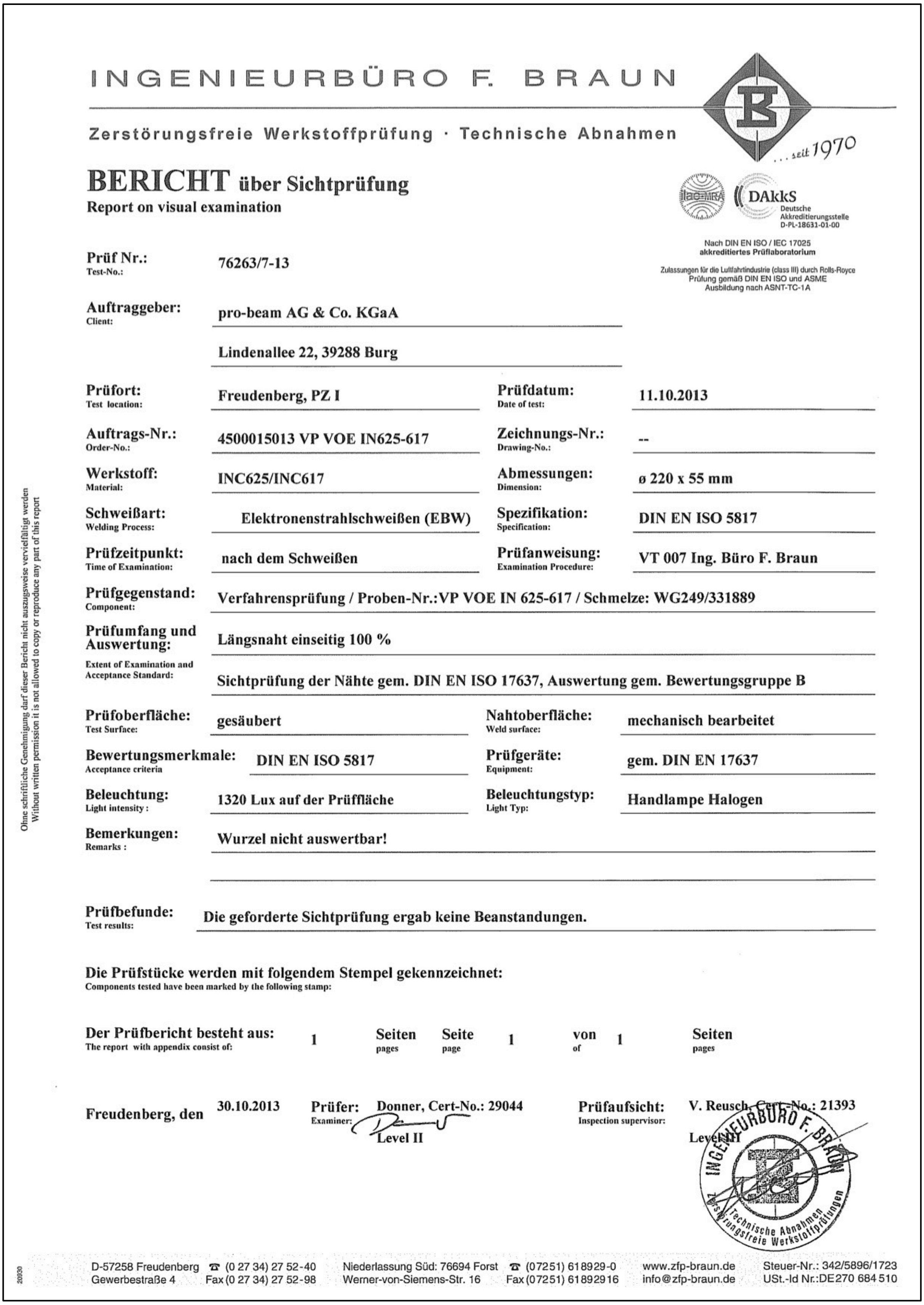
FIGURE 83: MACROSCOPY PRO-BEAM [43]



INGENIEURBÜRO F. BRAUN

Zerstörungsfreie Werkstoffprüfung · Technische Abnahmen

. . . seit 1970

BERICHT über Sichtprüfung
Report on visual examination

DAkkS
Deutsche
Akkreditierungsstelle
D-PL-18631-01-00

Nach DIN EN ISO / IEC 17025
akkreditiertes Prüflaboratorium

Zulassungen für die Luftfahrtindustrie (class III) durch Rolls-Royce
Prüfung gemäß DIN EN ISO und ASME
Ausbildung nach ASNT-TC-1A

Prüf Nr.: Test-No.: 76263/7-13

Auftraggeber: Client: pro-beam AG & Co. KGaA
Lindenallee 22, 39288 Burg

Prüfort: Test location: Freudenberg, PZ I
Prüfdatum: Date of test: 11.10.2013

Auftrags-Nr.: Order-No.: 4500015013 VP VOE IN625-617
Zeichnungs-Nr.: Drawing-No.: --

Werkstoff: Material: INC625/INC617
Abmessungen: Dimension: ø 220 x 55 mm

Schweißart: Welding Process: Elektronenstrahlschweißen (EBW)
Spezifikation: Specification: DIN EN ISO 5817

Prüfzeitpunkt: Time of Examination: nach dem Schweißen
Prüfanweisung: Examination Procedure: VT 007 Ing. Büro F. Braun

Prüfgegenstand: Component: Verfahrensprüfung / Proben-Nr.:VP VOE IN 625-617 / Schmelze: WG249/331889

Prüfumfang und Auswertung: Extent of Examination and Acceptance Standard: Längsnaht einseitig 100 %
Sichtprüfung der Nähte gem. DIN EN ISO 17637, Auswertung gem. Bewertungsgruppe B

Prüfoberfläche: Test Surface: gesäubert
Nahtoberfläche: Weld surface: mechanisch bearbeitet

Bewertungsmerkmale: Acceptance criteria: DIN EN ISO 5817
Prüfgeräte: Equipment: gem. DIN EN 17637

Beleuchtung: Light intensity : 1320 Lux auf der Prüffläche
Beleuchtungstyp: Light Typ: Handlampe Halogen

Bemerkungen: Remarks : Wurzel nicht auswertbar!

Prüfbefunde: Test results: Die geforderte Sichtprüfung ergab keine Beanstandungen.

Die Prüfstücke werden mit folgendem Stempel gekennzeichnet:
Components tested have been marked by the following stamp:

Der Prüfbericht besteht aus: The report with appendix consist of: 1 Seiten pages Seite page 1 von of 1 Seiten pages

Freudenberg, den 30.10.2013

Prüfer: Examiner: Donner, Cert-No.: 29044
Level II

Prüfaufsicht: Inspection supervisor: V. Reusch, Cert-No.: 21393
Level III

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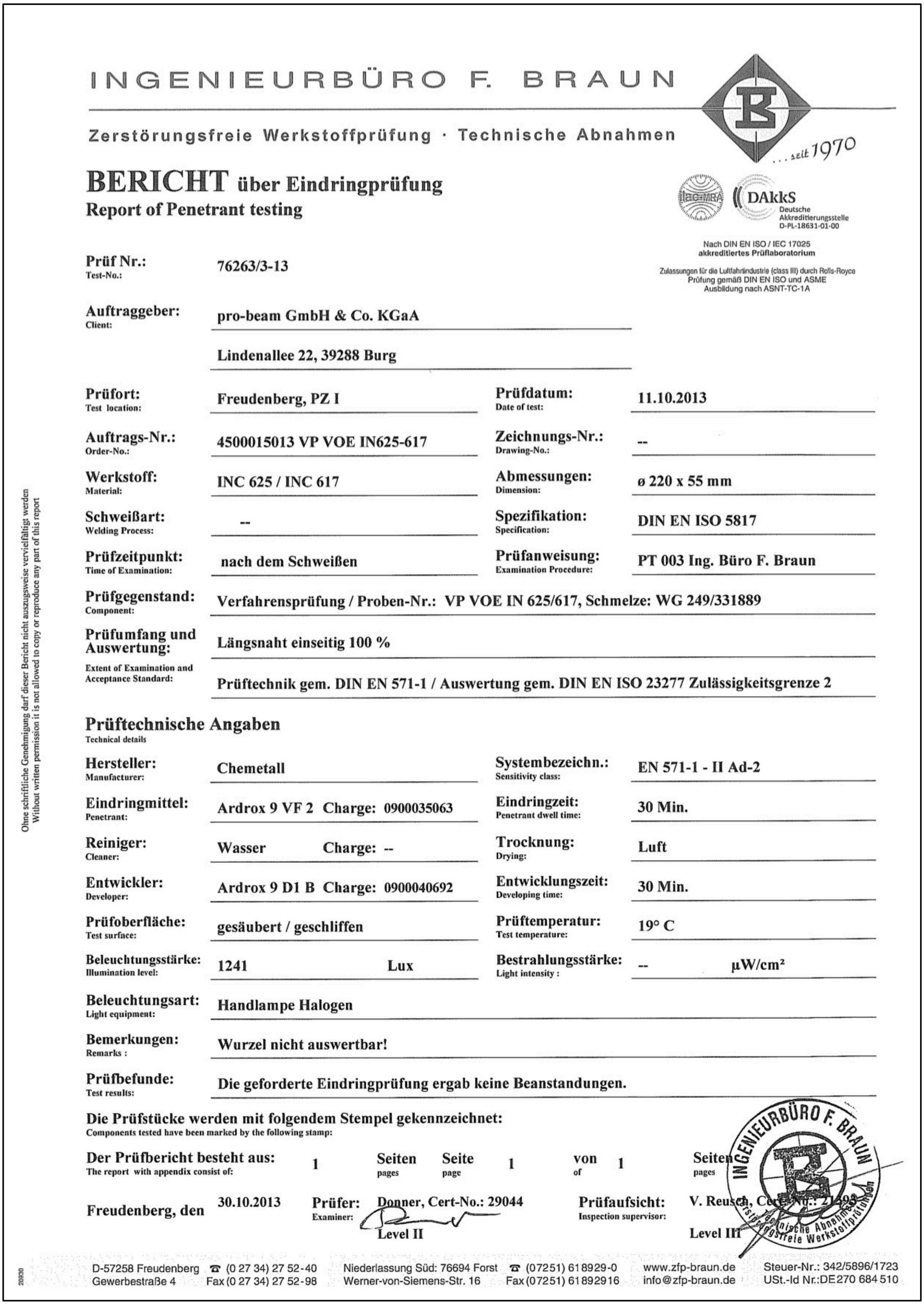
info@zfp-braun.de
Steuer-Nr.: 342/5896/1723
USt.-Id Nr.:DE270 684 510

20930

FIGURE 84: VISUAL TEST PRO-BEAM [43]



INGENIEURBÜRO F. BRAUN

Zerstörungsfreie Werkstoffprüfung · Technische Abnahmen

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Zulassungen für die Luftfahrtindustrie (class III) durch Rolls-Royce
Prüfung gemäß DIN EN ISO und ASME
Ausbildung nach ASNT-TC-1A

BERICHT über Eindringprüfung
Report of Penetrant testing

Prüf Nr.: Test-No.: 76263/3-13

Auftraggeber: Client: pro-beam GmbH & Co. KGaA
Lindenallee 22, 39288 Burg

Prüfort: Test location: Freudenberg, PZ I

Prüfdatum: Date of test: 11.10.2013

Auftrags-Nr.: Order-No.: 4500015013 VP VOE IN625-617

Zeichnungs-Nr.: Drawing-No.: --

Werkstoff: Material: INC 625 / INC 617

Abmessungen: Dimension: ø 220 x 55 mm

Schweißart: Welding Process: --

Spezifikation: Specification: DIN EN ISO 5817

Prüfzeitpunkt: Time of Examination: nach dem Schweißen

Prüfanweisung: Examination Procedure: PT 003 Ing. Büro F. Braun

Prüfgegenstand: Component: Verfahrensprüfung / Proben-Nr.: VP VOE IN 625/617, Schmelze: WG 249/331889

Prüfumfang und Auswertung: Extent of Examination and Acceptance Standard: Längsnaht einseitig 100 %
Prüftechnik gem. DIN EN 571-1 / Auswertung gem. DIN EN ISO 23277 Zulässigkeitsgrenze 2

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Prüftechnische Angaben
Technical details

Hersteller: Manufacturer: Chemetall

Systembezeichn.: Sensitivity class: EN 571-1 - II Ad-2

Eindringmittel: Penetrant: Ardrox 9 VF 2 Charge: 0900035063

Eindringzeit: Penetrant dwell time: 30 Min.

Reiniger: Cleaner: Wasser Charge: --

Trocknung: Drying: Luft

Entwickler: Developer: Ardrox 9 D1 B Charge: 0900040692

Entwicklungszeit: Developing time: 30 Min.

Prüfoberfläche: Test surface: gesäubert / geschliffen

Prüftemperatur: Test temperature: 19° C

Beleuchtungsstärke: Illumination level: 1241 Lux

Bestrahlungsstärke: Light intensity: -- µW/cm²

Beleuchtungsart: Light equipment: Handlampe Halogen

Bemerkungen: Remarks: Wurzel nicht auswertbar!

Prüfbefunde: Test results: Die geforderte Eindringprüfung ergab keine Beanstandungen.

Die Prüfstücke werden mit folgendem Stempel gekennzeichnet:
Components tested have been marked by the following stamp:

Der Prüfbericht besteht aus: The report with appendix consist of: 1 Seiten pages Seite page 1 von of 1 Seiten pages

Freudenberg, den 30.10.2013

Prüfer: Examiner: Donner, Cert-No.: 29044
Level II

Prüfaufsicht: Inspection supervisor: V. Reusch, Cert-No.: 21493
Level III

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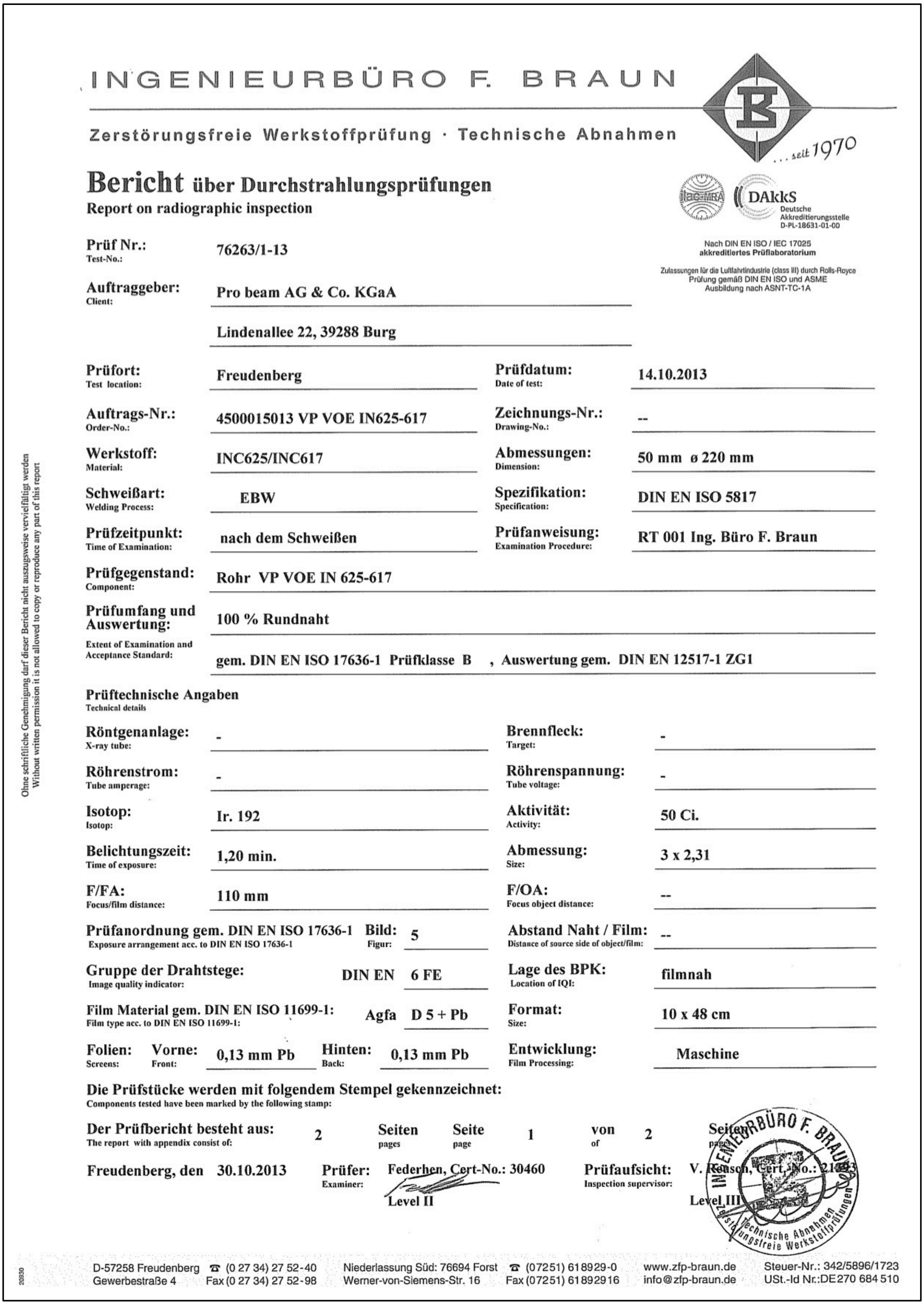
Steuer-Nr.: 342/5896/1723
USt.-Id Nr.:DE270 684 510

FIGURE 85: PENETRATION TEST PRO-BEAM [43]



INGENIEURBÜRO F. BRAUN

Zerstörungsfreie Werkstoffprüfung · Technische Abnahmen

... seit 1970

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Deutsche
Akkreditierungsstelle
D-PL-18631-01-00

Nach DIN EN ISO / IEC 17025
akkreditiertes Prüflaboratorium

Zulassungen für die Luftfahrtindustrie (class III) durch Rolls-Royce
Prüfung gemäß DIN EN ISO und ASME
Ausbildung nach ASNT-TC-1A

Bericht über Durchstrahlungsprüfungen
Report on radiographic inspection

Prüf Nr.: Test-No.: 76263/1-13

Auftraggeber: Client: Pro beam AG & Co. KGaA
Lindenallee 22, 39288 Burg

Prüfort: Test location: Freudenberg
Prüfdatum: Date of test: 14.10.2013

Auftrags-Nr.: Order-No.: 4500015013 VP VOE IN625-617
Zeichnungs-Nr.: Drawing-No.: --

Werkstoff: Material: INC625/INC617
Abmessungen: Dimension: 50 mm ø 220 mm

Schweißart: Welding Process: EBW
Spezifikation: Specification: DIN EN ISO 5817

Prüfzeitpunkt: Time of Examination: nach dem Schweißen
Prüfanweisung: Examination Procedure: RT 001 Ing. Büro F. Braun

Prüfgegenstand: Component: Rohr VP VOE IN 625-617

Prüfumfang und Auswertung: Extent of Examination and Acceptance Standard: 100 % Rundnaht
gem. DIN EN ISO 17636-1 Prüfklasse B , Auswertung gem. DIN EN 12517-1 ZG1

Prüftechnische Angaben
Technical details

Röntgenanlage: X-ray tube: -
Brennfleck: Target: -

Röhrenstrom: Tube amperage: -
Röhrenspannung: Tube voltage: -

Isotop: Isotop: Ir. 192
Aktivität: Activity: 50 Ci.

Belichtungszeit: Time of exposure: 1,20 min.
Abmessung: Size: 3 x 2,31

F/FA: Focus/film distance: 110 mm
F/OA: Focus object distance: --

Prüfanordnung gem. DIN EN ISO 17636-1 Exposure arrangement acc. to DIN EN ISO 17636-1 **Bild:** Figur: 5
Abstand Naht / Film: Distance of source side of object/film: --

Gruppe der Drahtstege: Image quality indicator: DIN EN 6 FE
Lage des BPK: Location of IQI: filmnah

Film Material gem. DIN EN ISO 11699-1: Film type acc. to DIN EN ISO 11699-1: Agfa D 5 + Pb
Format: Size: 10 x 48 cm

Folien: Screens: **Vorne:** Front: 0,13 mm Pb **Hinten:** Back: 0,13 mm Pb
Entwicklung: Film Processing: Maschine

Die Prüfstücke werden mit folgendem Stempel gekennzeichnet:
Components tested have been marked by the following stamp:

Der Prüfbericht besteht aus: The report with appendix consist of: 2 **Seiten** pages **Seite** page 1 **von** of 2 **Seiten** pages

Freudenberg, den 30.10.2013
Prüfer: Examiner: Federhen, Cert-No.: 30460
Level II
Prüfaufsicht: Inspection supervisor: V. Reusch, Cert, No.: 21[illegible]
Level III

INGENIEURBÜRO F. BRAUN
Technische Abnahmen
Zerstörungsfreie Werkstoffprüfungen

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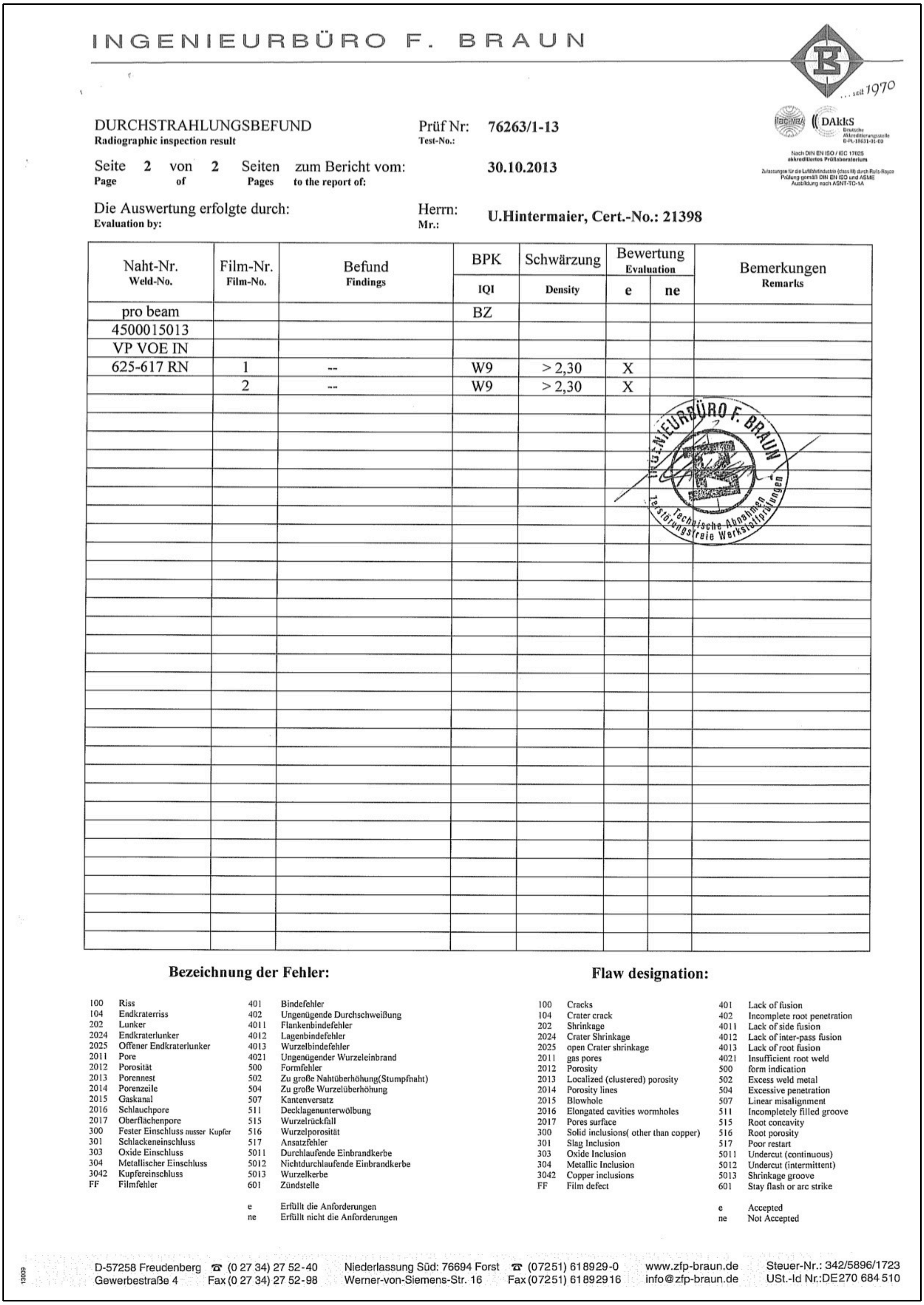
www.zfp-braun.de
info@zfp-braun.de
Steuer-Nr.: 342/5896/1723
USt.-Id Nr.:DE270 684 510

20930

FIGURE 86: RADIOGRAPHIC TEST PRO-BEAM PAGE 1/2 [43]



INGENIEURBÜRO F. BRAUN

... seit 1970

DAkkS
Deutsche
Akkreditierungsstelle
D-PL-18631-01-00

Nach DIN EN ISO / IEC 17025
akkreditiertes Prüflaboratorium

Zulassungen für die Luftfahrtindustrie (class III) durch Rolls-Royce
Prüfung gemäß DIN EN ISO und ASME
Ausbildung nach ASNT-TC-1A

DURCHSTRAHLUNGSBEFUND
Radiographic inspection result

Prüf Nr: / Test-No.: **76263/1-13**

Seite **2** von **2** Seiten zum Bericht vom: / Page of Pages to the report of: **30.10.2013**

Die Auswertung erfolgte durch: / Evaluation by: Herrn: / Mr.: **U.Hintermaier, Cert.-No.: 21398**

Naht-Nr. Weld-No.	Film-Nr. Film-No.	Befund Findings	BPK	Schwärzung	Bewertung Evaluation		Bemerkungen Remarks
			IQI	Density	e	ne	
pro beam			BZ				
4500015013							
VP VOE IN							
625-617 RN	1	--	W9	> 2,30	X		
	2	--	W9	> 2,30	X		

INGENIEURBÜRO F. BRAUN
Technische Abnahmen
Zerstörungsfreie Werkstoffprüfungen

Bezeichnung der Fehler:

100	Riss	401	Bindefehler
104	Endkraterriss	402	Ungenügende Durchschweißung
202	Lunker	4011	Flankenbindefehler
2024	Endkraterlunker	4012	Lagenbindefehler
2025	Offener Endkraterlunker	4013	Wurzelbindefehler
2011	Pore	4021	Ungenügender Wurzeleinbrand
2012	Porosität	500	Formfehler
2013	Porennest	502	Zu große Nahtüberhöhung(Stumpfnaht)
2014	Porenzeile	504	Zu große Wurzelüberhöhung
2015	Gaskanal	507	Kantenversatz
2016	Schlauchpore	511	Decklagenunterwölbung
2017	Oberflächenpore	515	Wurzelrückfall
300	Fester Einschluss ausser Kupfer	516	Wurzelporosität
301	Schlackeneinschluss	517	Ansatzfehler
303	Oxide Einschluss	5011	Durchlaufende Einbrandkerbe
304	Metallischer Einschluss	5012	Nichtdurchlaufende Einbrandkerbe
3042	Kupfereinschluss	5013	Wurzelkerbe
FF	Filmfehler	601	Zündstelle
		e	Erfüllt die Anforderungen
		ne	Erfüllt nicht die Anforderungen

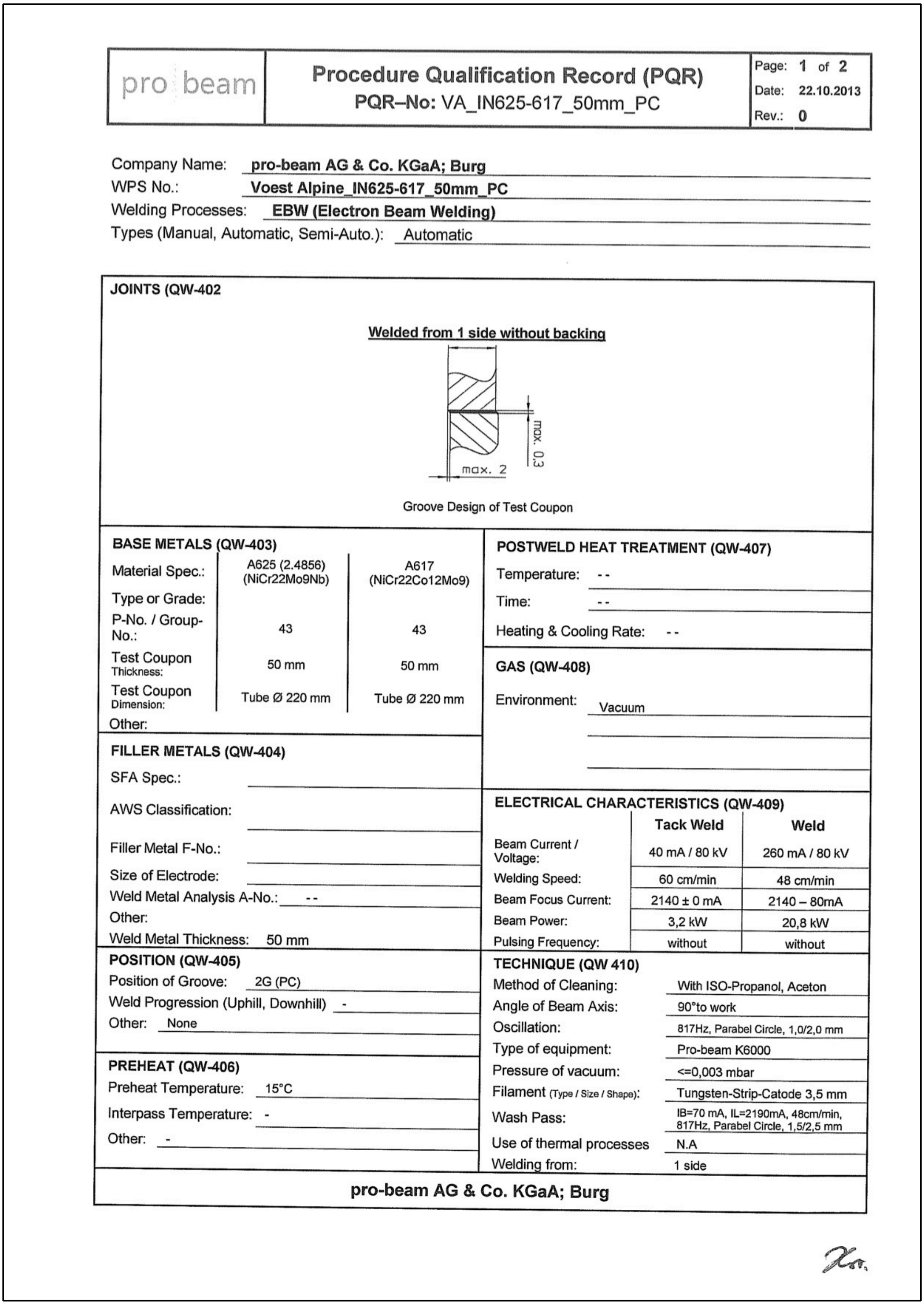
Flaw designation:

100	Cracks	401	Lack of fusion
104	Crater crack	402	Incomplete root penetration
202	Shrinkage	4011	Lack of side fusion
2024	Crater Shrinkage	4012	Lack of inter-pass fusion
2025	open Crater shrinkage	4013	Lack of root fusion
2011	gas pores	4021	Insufficient root weld
2012	Porosity	500	form indication
2013	Localized (clustered) porosity	502	Excess weld metal
2014	Porosity lines	504	Excessive penetration
2015	Blowhole	507	Linear misalignment
2016	Elongated cavities wormholes	511	Incompletely filled groove
2017	Pores surface	515	Root concavity
300	Solid inclusions(other than copper)	516	Root porosity
301	Slag Inclusion	517	Poor restart
303	Oxide Inclusion	5011	Undercut (continuous)
304	Metallic Inclusion	5012	Undercut (intermittent)
3042	Copper inclusions	5013	Shrinkage groove
FF	Film defect	601	Stay flash or arc strike
		e	Accepted
		ne	Not Accepted

13009

D-57258 Freudenberg ☎ (0 27 34) 27 52-40 Niederlassung Süd: 76694 Forst ☎ (07251) 618929-0 www.zfp-braun.de Steuer-Nr.: 342/5896/1723
Gewerbestraße 4 Fax (0 27 34) 27 52-98 Werner-von-Siemens-Str. 16 Fax (07251) 61892916 info@zfp-braun.de USt.-Id Nr.:DE270 684 510

FIGURE 87: RADIOGRAPHIC TEST PRO-BEAM PAGE 2/2 [43]



pro beam

Procedure Qualification Record (PQR)

PQR–No: VA_IN625-617_50mm_PC

Page: **1** of **2**
Date: **22.10.2013**
Rev.: **0**

Company Name: **pro-beam AG & Co. KGaA; Burg**
WPS No.: **Voest Alpine_IN625-617_50mm_PC**
Welding Processes: **EBW (Electron Beam Welding)**
Types (Manual, Automatic, Semi-Auto.): Automatic

JOINTS (QW-402

Welded from 1 side without backing

Groove Design of Test Coupon

BASE METALS (QW-403)

Material Spec.:	A625 (2.4856) (NiCr22Mo9Nb)	A617 (NiCr22Co12Mo9)
Type or Grade:		
P-No. / Group-No.:	43	43
Test Coupon Thickness:	50 mm	50 mm
Test Coupon Dimension:	Tube Ø 220 mm	Tube Ø 220 mm
Other:		

FILLER METALS (QW-404)

SFA Spec.:
AWS Classification:
Filler Metal F-No.:
Size of Electrode:
Weld Metal Analysis A-No.: - -
Other:
Weld Metal Thickness: 50 mm

POSITION (QW-405)

Position of Groove: 2G (PC)
Weld Progression (Uphill, Downhill) -
Other: None

PREHEAT (QW-406)

Preheat Temperature: 15°C
Interpass Temperature: -
Other: -

POSTWELD HEAT TREATMENT (QW-407)

Temperature: - -
Time: - -
Heating & Cooling Rate: - -

GAS (QW-408)

Environment: Vacuum

ELECTRICAL CHARACTERISTICS (QW-409)

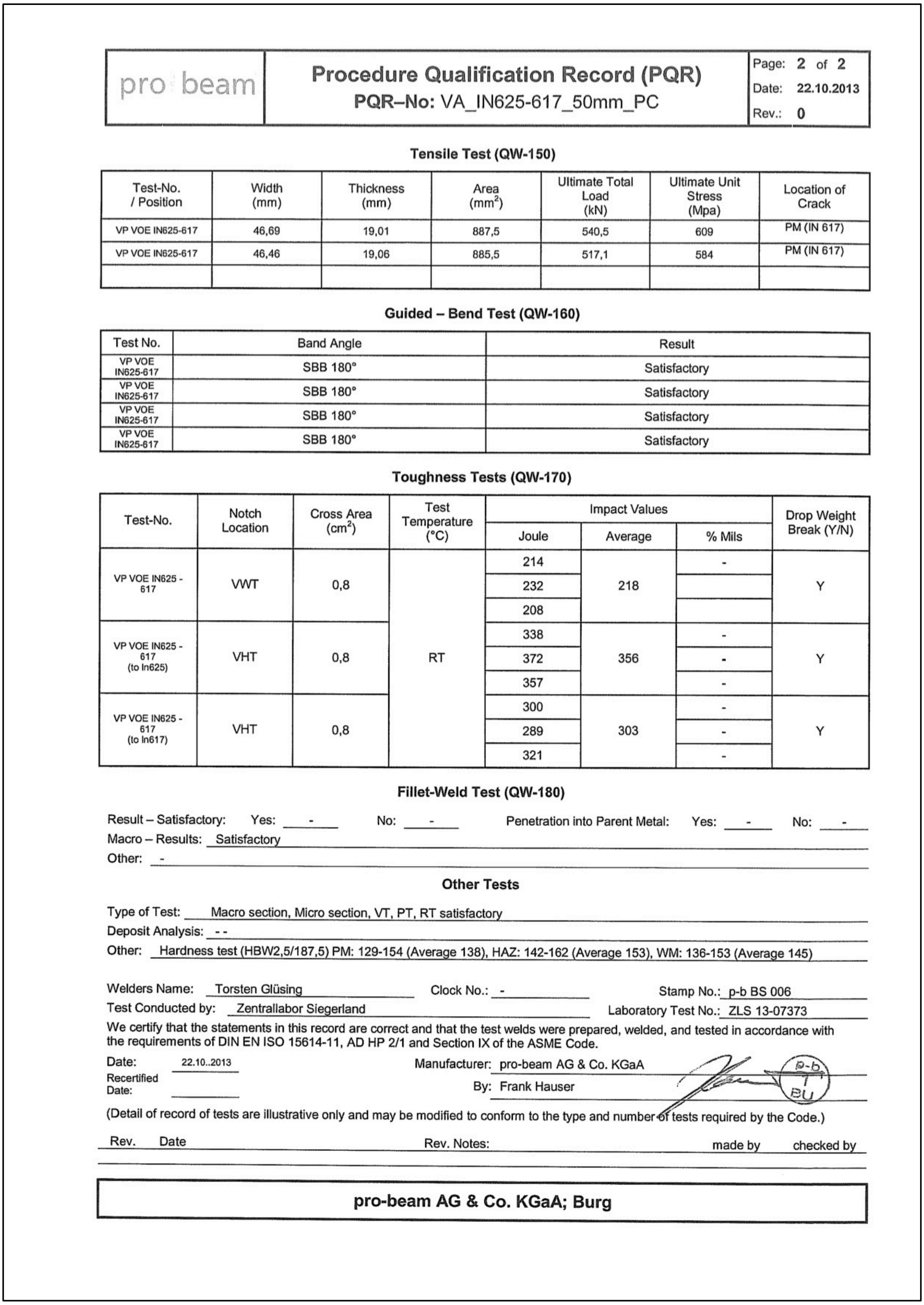
	Tack Weld	**Weld**
Beam Current / Voltage:	40 mA / 80 kV	260 mA / 80 kV
Welding Speed:	60 cm/min	48 cm/min
Beam Focus Current:	2140 ± 0 mA	2140 – 80mA
Beam Power:	3,2 kW	20,8 kW
Pulsing Frequency:	without	without

TECHNIQUE (QW 410)

Method of Cleaning: With ISO-Propanol, Aceton
Angle of Beam Axis: 90°to work
Oscillation: 817Hz, Parabel Circle, 1,0/2,0 mm
Type of equipment: Pro-beam K6000
Pressure of vacuum: <=0,003 mbar
Filament (Type / Size / Shape): Tungsten-Strip-Catode 3,5 mm
Wash Pass: IB=70 mA, IL=2190mA, 48cm/min, 817Hz, Parabel Circle, 1,5/2,5 mm
Use of thermal processes N.A
Welding from: 1 side

pro-beam AG & Co. KGaA; Burg

FIGURE 88: PQR PRO-BEAM PAGE 1/2 [43]



pro beam

Procedure Qualification Record (PQR)

PQR–No: VA_IN625-617_50mm_PC

Page: **2** of **2**
Date: **22.10.2013**
Rev.: **0**

Tensile Test (QW-150)

Test-No. / Position	Width (mm)	Thickness (mm)	Area (mm^2)	Ultimate Total Load (kN)	Ultimate Unit Stress (Mpa)	Location of Crack
VP VOE IN625-617	46,69	19,01	887,5	540,5	609	PM (IN 617)
VP VOE IN625-617	46,46	19,06	885,5	517,1	584	PM (IN 617)

Guided – Bend Test (QW-160)

Test No.	Band Angle	Result
VP VOE IN625-617	SBB 180°	Satisfactory
VP VOE IN625-617	SBB 180°	Satisfactory
VP VOE IN625-617	SBB 180°	Satisfactory
VP VOE IN625-617	SBB 180°	Satisfactory

Toughness Tests (QW-170)

Test-No.	Notch Location	Cross Area (cm^2)	Test Temperature (°C)	Impact Values			Drop Weight Break (Y/N)
				Joule	Average	% Mils	
VP VOE IN625 - 617	VWT	0,8	RT	214	218	-	Y
				232			
				208			
VP VOE IN625 - 617 (to In625)	VHT	0,8		338	356	-	Y
				372		-	
				357		-	
VP VOE IN625 - 617 (to In617)	VHT	0,8		300	303	-	Y
				289		-	
				321		-	

Fillet-Weld Test (QW-180)

Result – Satisfactory: Yes: - No: - Penetration into Parent Metal: Yes: - No: -
Macro – Results: Satisfactory
Other: -

Other Tests

Type of Test: Macro section, Micro section, VT, PT, RT satisfactory
Deposit Analysis: - -
Other: Hardness test (HBW2,5/187,5) PM: 129-154 (Average 138), HAZ: 142-162 (Average 153), WM: 136-153 (Average 145)

Welders Name: Torsten Glüsing Clock No.: - Stamp No.: p-b BS 006
Test Conducted by: Zentrallabor Siegerland Laboratory Test No.: ZLS 13-07373

We certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of DIN EN ISO 15614-11, AD HP 2/1 and Section IX of the ASME Code.

Date: 22.10..2013 Manufacturer: pro-beam AG & Co. KGaA
Recertified Date: By: Frank Hauser

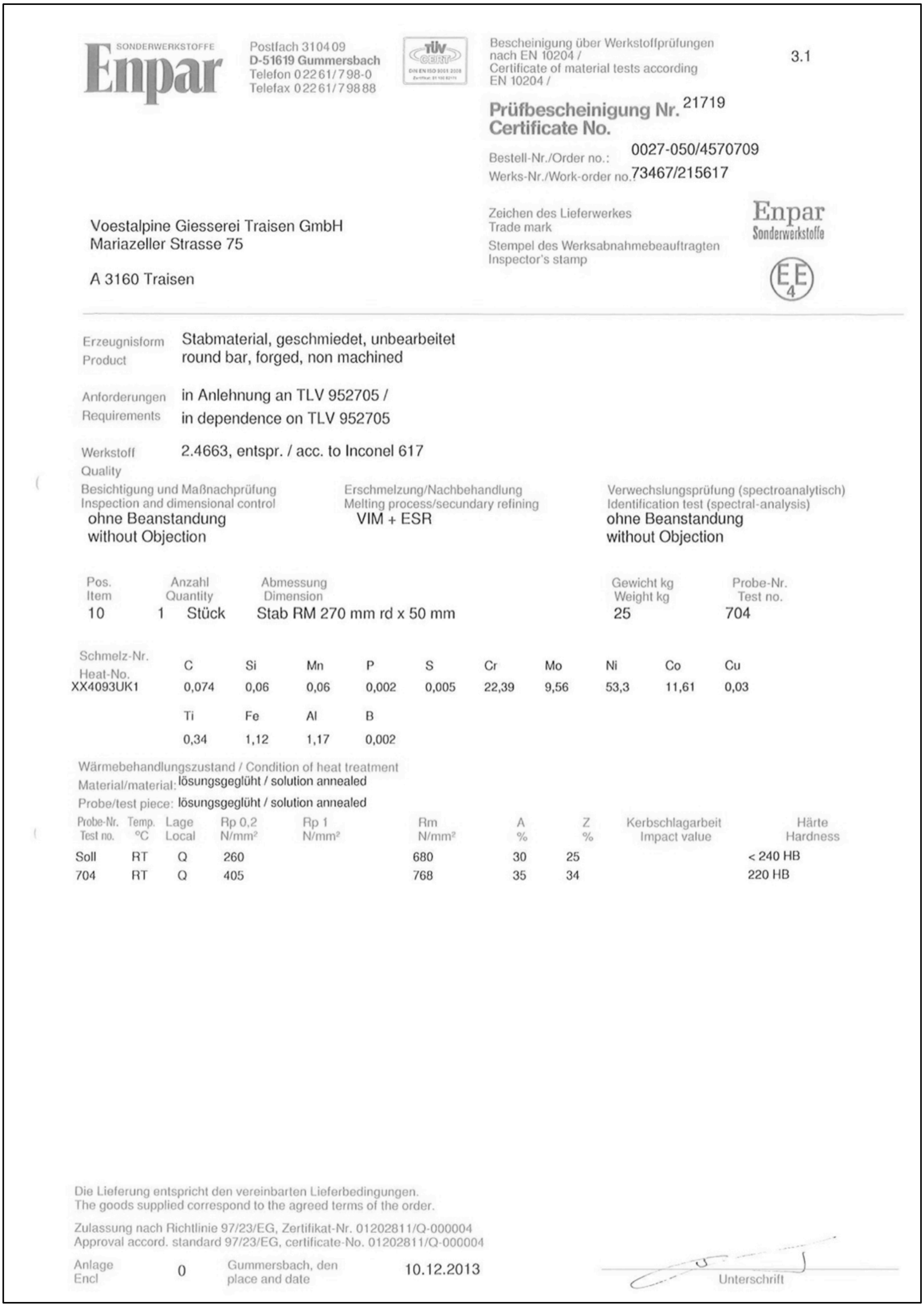
p-b 7 BU

(Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

Rev. Date Rev. Notes: made by checked by

pro-beam AG & Co. KGaA; Burg

FIGURE 89: PQR PRO-BEAM PAGE 2/2 [43]



SONDERWERKSTOFFE
Enpar

Postfach 310409
D-51619 Gummersbach
Telefon 02261/798-0
Telefax 02261/79888

TÜV CERT
DIN EN ISO 9001:2008

Bescheinigung über Werkstoffprüfungen
nach EN 10204 /
Certificate of material tests according
EN 10204 /

3.1

Prüfbescheinigung Nr. 21719
Certificate No.

Bestell-Nr./Order no.: 0027-050/4570709
Werks-Nr./Work-order no. 73467/215617

Voestalpine Giesserei Traisen GmbH
Mariazeller Strasse 75

A 3160 Traisen

Zeichen des Lieferwerkes
Trade mark
Stempel des Werksabnahmebeauftragten
Inspector's stamp

Enpar
Sonderwerkstoffe

E E 4

Erzeugnisform / Product: Stabmaterial, geschmiedet, unbearbeitet
round bar, forged, non machined

Anforderungen / Requirements: in Anlehnung an TLV 952705 /
in dependence on TLV 952705

Werkstoff / Quality: 2.4663, entspr. / acc. to Inconel 617

Besichtigung und Maßnachprüfung Inspection and dimensional control	Erschmelzung/Nachbehandlung Melting process/secundary refining	Verwechslungsprüfung (spectroanalytisch) Identification test (spectral-analysis)
ohne Beanstandung without Objection	VIM + ESR	ohne Beanstandung without Objection

Pos. Item	Anzahl Quantity	Abmessung Dimension	Gewicht kg Weight kg	Probe-Nr. Test no.
10	1 Stück	Stab RM 270 mm rd x 50 mm	25	704

Schmelz-Nr. Heat-No.	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu
XX4093UK1	0,074	0,06	0,06	0,002	0,005	22,39	9,56	53,3	11,61	0,03

	Ti	Fe	Al	B
	0,34	1,12	1,17	0,002

Wärmebehandlungszustand / Condition of heat treatment
Material/material: lösungsgeglüht / solution annealed
Probe/test piece: lösungsgeglüht / solution annealed

Probe-Nr. Test no.	Temp. °C	Lage Local	Rp 0,2 N/mm²	Rp 1 N/mm²	Rm N/mm²	A %	Z %	Kerbschlagarbeit Impact value	Härte Hardness
Soll	RT	Q	260		680	30	25		< 240 HB
704	RT	Q	405		768	35	34		220 HB

Die Lieferung entspricht den vereinbarten Lieferbedingungen.
The goods supplied correspond to the agreed terms of the order.

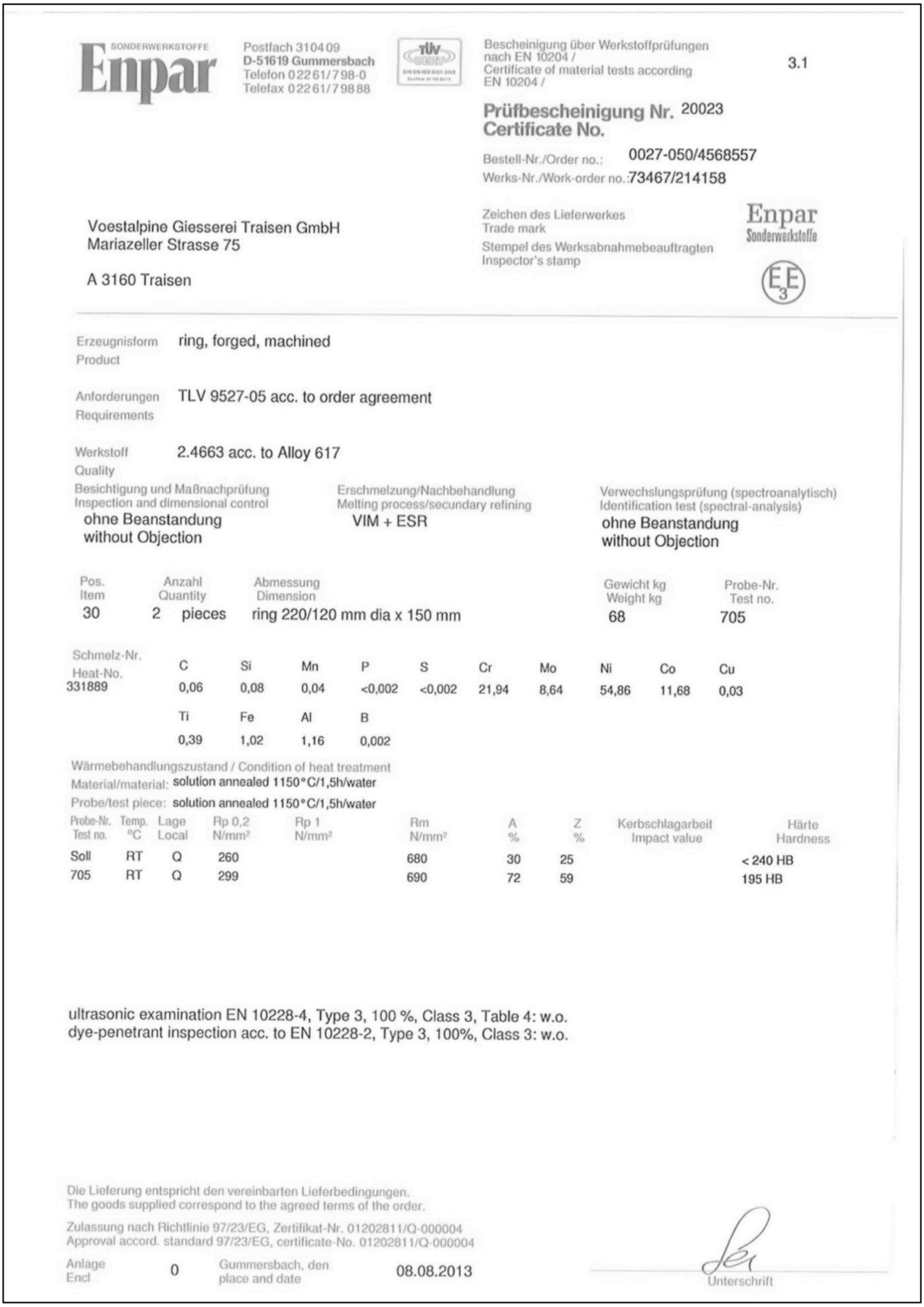
Zulassung nach Richtlinie 97/23/EG, Zertifikat-Nr. 01202811/Q-000004
Approval accord. standard 97/23/EG, certificate-No. 01202811/Q-000004

Anlage / Encl: 0

Gummersbach, den / place and date: 10.12.2013

Unterschrift

FIGURE 90: MATERIAL CERTIFICATE - ALLOY 617 - SMAW



SONDERWERKSTOFFE
Enpar

Postfach 310409
D-51619 Gummersbach
Telefon 02261/798-0
Telefax 02261/79888

Bescheinigung über Werkstoffprüfungen nach EN 10204 /
Certificate of material tests according EN 10204 / 3.1

Prüfbescheinigung Nr. 20023
Certificate No.

Bestell-Nr./Order no.: 0027-050/4568557
Werks-Nr./Work-order no.: 73467/214158

Voestalpine Giesserei Traisen GmbH
Mariazeller Strasse 75

A 3160 Traisen

Zeichen des Lieferwerkes
Trade mark
Enpar
Sonderwerkstoffe

Stempel des Werksabnahmebeauftragten
Inspector's stamp
E E 3

Erzeugnisform / Product: ring, forged, machined

Anforderungen / Requirements: TLV 9527-05 acc. to order agreement

Werkstoff / Quality: 2.4663 acc. to Alloy 617

Besichtigung und Maßnachprüfung Inspection and dimensional control	Erschmelzung/Nachbehandlung Melting process/secundary refining	Verwechslungsprüfung (spectroanalytisch) Identification test (spectral-analysis)
ohne Beanstandung without Objection	VIM + ESR	ohne Beanstandung without Objection

Pos. Item	Anzahl Quantity	Abmessung Dimension	Gewicht kg Weight kg	Probe-Nr. Test no.
30	2 pieces	ring 220/120 mm dia x 150 mm	68	705

Schmelz-Nr. Heat-No.	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu
331889	0,06	0,08	0,04	<0,002	<0,002	21,94	8,64	54,86	11,68	0,03
	Ti	Fe	Al	B						
	0,39	1,02	1,16	0,002						

Wärmebehandlungszustand / Condition of heat treatment
Material/material: solution annealed 1150°C/1,5h/water
Probe/test piece: solution annealed 1150°C/1,5h/water

Probe-Nr. Test no.	Temp. °C	Lage Local	Rp 0,2 N/mm²	Rp 1 N/mm²	Rm N/mm²	A %	Z %	Kerbschlagarbeit Impact value	Härte Hardness
Soll	RT	Q	260		680	30	25		< 240 HB
705	RT	Q	299		690	72	59		195 HB

ultrasonic examination EN 10228-4, Type 3, 100 %, Class 3, Table 4: w.o.
dye-penetrant inspection acc. to EN 10228-2, Type 3, 100%, Class 3: w.o.

Die Lieferung entspricht den vereinbarten Lieferbedingungen.
The goods supplied correspond to the agreed terms of the order.

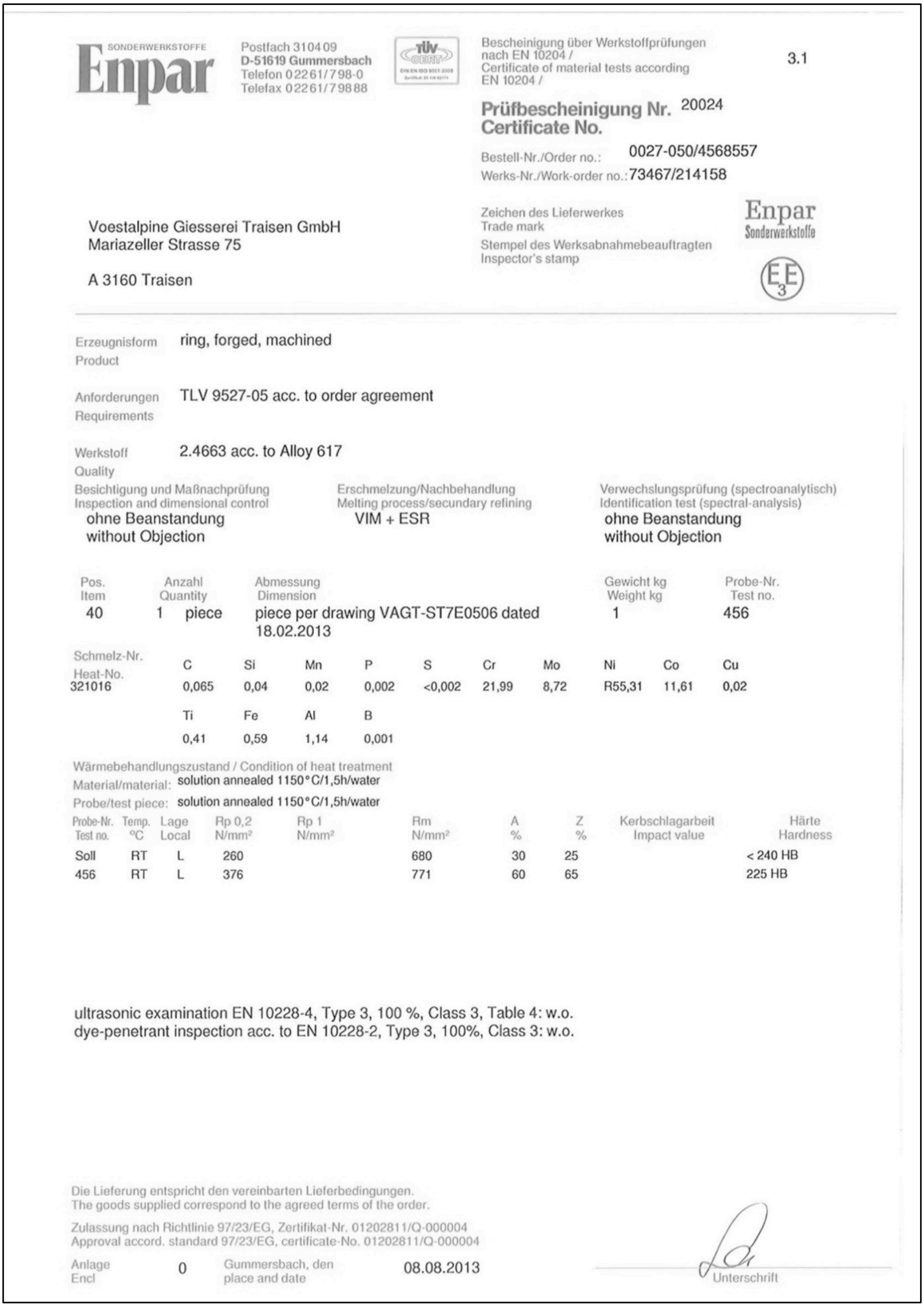
Zulassung nach Richtlinie 97/23/EG, Zertifikat-Nr. 01202811/Q-000004
Approval accord. standard 97/23/EG, certificate-No. 01202811/Q-000004

Anlage / Encl 0

Gummersbach, den / place and date 08.08.2013

Unterschrift

FIGURE 91: MATERIAL CERTIFICATE - ALLOY 617 - EBW



SONDERWERKSTOFFE
Enpar

Postfach 310409
D-51619 Gummersbach
Telefon 02261/798-0
Telefax 02261/79888

TÜV CERT DIN EN ISO 9001:2008

Bescheinigung über Werkstoffprüfungen
nach EN 10204 /
Certificate of material tests according
EN 10204 /

3.1

Prüfbescheinigung Nr. 20024
Certificate No.

Bestell-Nr./Order no.: 0027-050/4568557
Werks-Nr./Work-order no.: 73467/214158

Voestalpine Giesserei Traisen GmbH
Mariazeller Strasse 75

A 3160 Traisen

Zeichen des Lieferwerkes
Trade mark
Stempel des Werksabnahmebeauftragten
Inspector's stamp

Enpar
Sonderwerkstoffe

E E 3

Erzeugnisform
Product
ring, forged, machined

Anforderungen
Requirements
TLV 9527-05 acc. to order agreement

Werkstoff
Quality
2.4663 acc. to Alloy 617

Besichtigung und Maßnachprüfung Inspection and dimensional control	Erschmelzung/Nachbehandlung Melting process/secundary refining	Verwechslungsprüfung (spectroanalytisch) Identification test (spectral-analysis)
ohne Beanstandung without Objection	VIM + ESR	ohne Beanstandung without Objection

Pos. Item	Anzahl Quantity	Abmessung Dimension	Gewicht kg Weight kg	Probe-Nr. Test no.
40	1 piece	piece per drawing VAGT-ST7E0506 dated 18.02.2013	1	456

Schmelz-Nr. Heat-No.	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Cu
321016	0,065	0,04	0,02	0,002	<0,002	21,99	8,72	R55,31	11,61	0,02

	Ti	Fe	Al	B
	0,41	0,59	1,14	0,001

Wärmebehandlungszustand / Condition of heat treatment
Material/material: solution annealed 1150°C/1,5h/water
Probe/test piece: solution annealed 1150°C/1,5h/water

Probe-Nr. Test no.	Temp. °C	Lage Local	Rp 0,2 N/mm^2	Rp 1 N/mm^2	Rm N/mm^2	A %	Z %	Kerbschlagarbeit Impact value	Härte Hardness
Soll	RT	L	260		680	30	25		< 240 HB
456	RT	L	376		771	60	65		225 HB

ultrasonic examination EN 10228-4, Type 3, 100 %, Class 3, Table 4: w.o.
dye-penetrant inspection acc. to EN 10228-2, Type 3, 100%, Class 3: w.o.

Die Lieferung entspricht den vereinbarten Lieferbedingungen.
The goods supplied correspond to the agreed terms of the order.

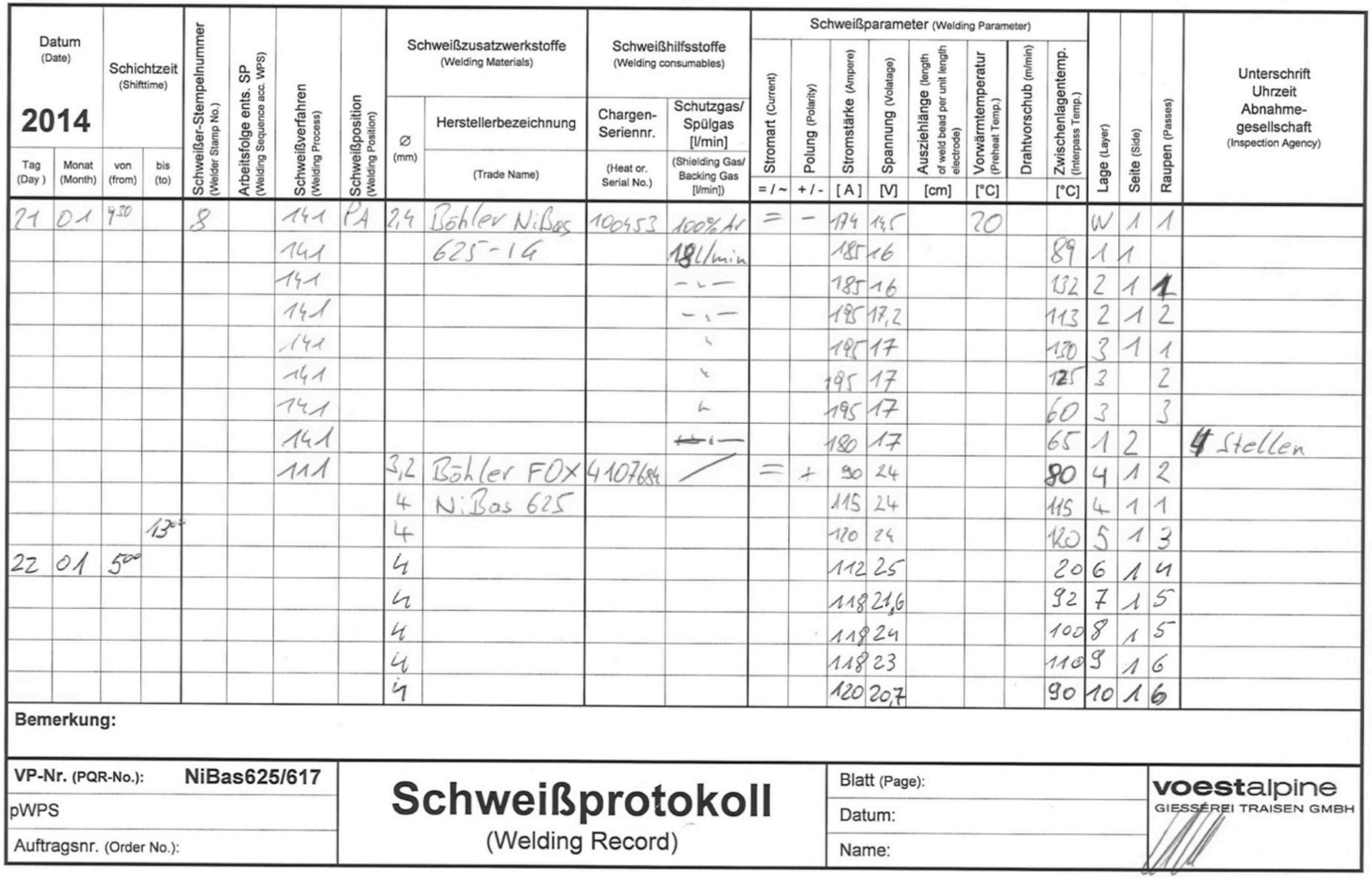
Zulassung nach Richtlinie 97/23/EG, Zertifikat-Nr. 01202811/Q-000004
Approval accord. standard 97/23/EG, certificate-No. 01202811/Q-000004

Anlage
Encl
0

Gummersbach, den
place and date
08.08.2013

Unterschrift

FIGURE 92: MATERIAL CERTIFICATE – ALLOY 617 - SMAW



Datum (Date) 2014 Tag (Day)	Monat (Month)	Schichtzeit (Shifttime) von (from)	bis (to)	Schweißer-Stempelnummer (Welder Stamp No.)	Arbeitsfolge ents. SP (Welding Sequence acc. WPS)	Schweißverfahren (Welding Process)	Schweißposition (Welding Position)	Schweißzusatzwerkstoffe (Welding Materials) Ø (mm)	Herstellerbezeichnung (Trade Name)	Schweißhilfsstoffe (Welding consumables) Chargen-Seriennr. (Heat or. Serial No.)	Schutzgas/ Spülgas [l/min] (Shielding Gas/ Backing Gas [l/min])	Schweißparameter (Welding Parameter) Stromart (Current) = / ~	Polung (Polarity) + / -	Stromstärke (Ampere) [A]	Spannung (Volatage) [V]	Ausziehlänge (length of weld bead per unit length electrode) [cm]	Vorwärmtemperatur (Preheat Temp.) [°C]	Drahtvorschub (m/min)	Zwischenlagentemp. (Interpass Temp.) [°C]	Lage (Layer)	Seite (Side)	Raupen (Passes)	Unterschrift Uhrzeit Abnahme-gesellschaft (Inspection Agency)
21	01	9^{30}		8		141	PA	2,4	Böhler NiBas	100453	100% Ar	=	−	174	14,5		20			W	1	1	
						141			625-1G		18l/min			185	16				89	1	1		
						141					-"-			185	16				132	2	1	1	
						141					-"-			195	17,2				113	2	1	2	
						141					"			195	17				130	3	1	1	
						141					"			195	17				125	3		2	
						141					"			195	17				60	3		3	
						141					-"-			180	17				65	1	2		4 Stellen
						111		3,2	Böhler FOX	4107684	/	=	+	90	24				80	4	1	2	
								4	NiBas 625					115	24				115	4	1	1	
			13^{00}					4						120	24				120	5	1	3	
22	01	5^{00}						4						112	25				20	6	1	4	
								4						118	21,6				92	7	1	5	
								4						118	24				100	8	1	5	
								4						118	23				110	9	1	6	
								4						120	20,7				90	10	1	6	

Bemerkung:

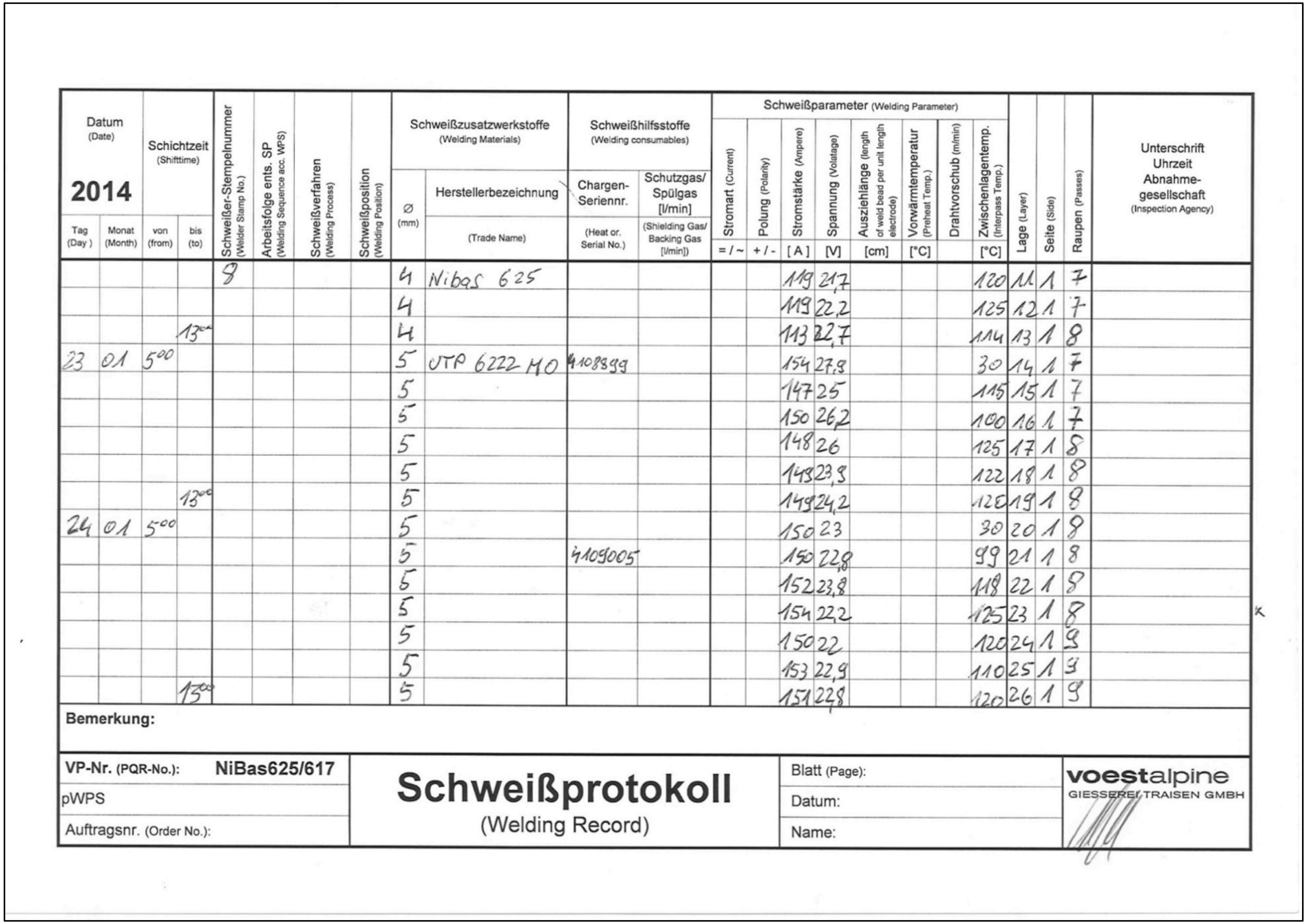
VP-Nr. (PQR-No.): **NiBas625/617**
pWPS
Auftragsnr. (Order No.):

Schweißprotokoll
(Welding Record)

Blatt (Page):
Datum:
Name:

voestalpine
GIESSEREI TRAISEN GMBH

FIGURE 93: WELDING RECORD - SMAW - PAGE 1



Datum (Date) 2014		Schichtzeit (Shifttime)		Schweißer-Stempelnummer (Welder Stamp No.)	Arbeitsfolge ents. SP (Welding Sequence acc. WPS)	Schweißverfahren (Welding Process)	Schweißposition (Welding Position)	Schweißzusatzwerkstoffe (Welding Materials)		Schweißhilfsstoffe (Welding consumables)		Schweißparameter (Welding Parameter)								Lage (Layer)	Seite (Side)	Raupen (Passes)	Unterschrift Uhrzeit Abnahme-gesellschaft (Inspection Agency)
Tag (Day)	Monat (Month)	von (from)	bis (to)					Ø (mm)	Herstellerbezeichnung (Trade Name)	Chargen-Seriennr. (Heat or. Serial No.)	Schutzgas/ Spülgas [l/min] (Shielding Gas/ Backing Gas [l/min])	Stromart (Current) = / ~	Polung (Polarity) + / -	Stromstärke (Ampere) [A]	Spannung (Volatage) [V]	Ausziehlänge (length of weld bead per unit length electrode) [cm]	Vorwärmtemperatur (Preheat Temp.) [°C]	Drahtvorschub (m/min)	Zwischenlagentemp. (Interpass Temp.) [°C]				
				8				4	Nibas 625					119	21,7				120	11	1	7	
								4						119	22,2				125	12	1	7	
			13^{00}					4						113	22,7				114	13	1	8	
23	01	5^{00}						5	UTP 6222 MO	4108399				154	27,9				30	14	1	7	
								5						147	25				115	15	1	7	
								5						150	26,2				100	16	1	7	
								5						148	26				125	17	1	8	
								5						149	23,9				122	18	1	8	
			13^{00}					5						149	24,2				125	19	1	8	
24	01	5^{00}						5						150	23				30	20	1	8	
								5		4109005				150	22,8				99	21	1	8	
								5						152	23,8				118	22	1	8	
								5						154	22,2				125	23	1	8	
								5						150	22				120	24	1	9	
								5						153	22,9				110	25	1	9	
			13^{00}					5						151	22,8				120	26	1	9	

Bemerkung:

VP-Nr. (PQR-No.): NiBas625/617

pWPS

Auftragsnr. (Order No.):

Schweißprotokoll

(Welding Record)

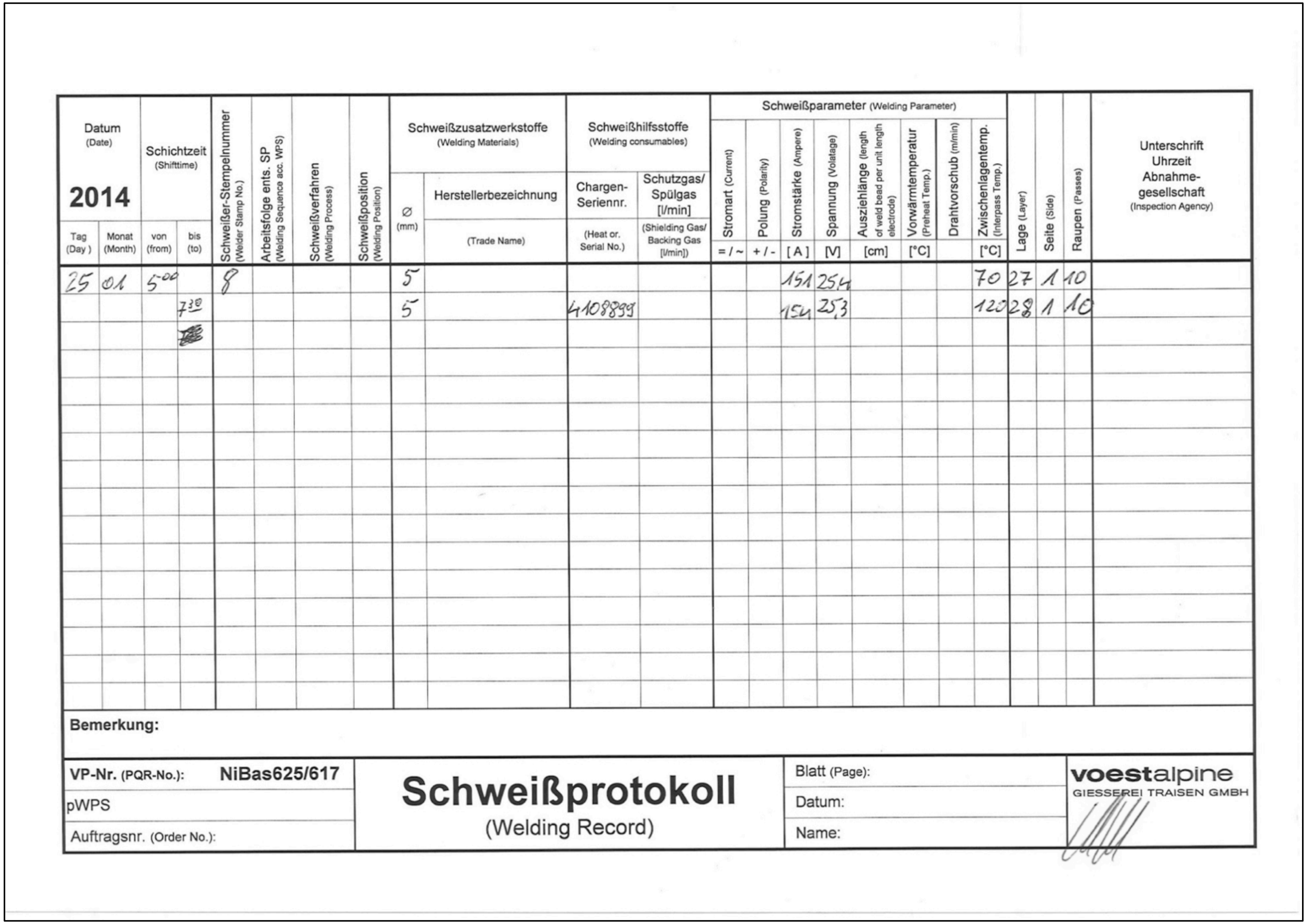
Blatt (Page):

Datum:

Name:

voestalpine GIESSEREI TRAISEN GMBH

FIGURE 94: WELDING RECORD - SMAW - PAGE 2

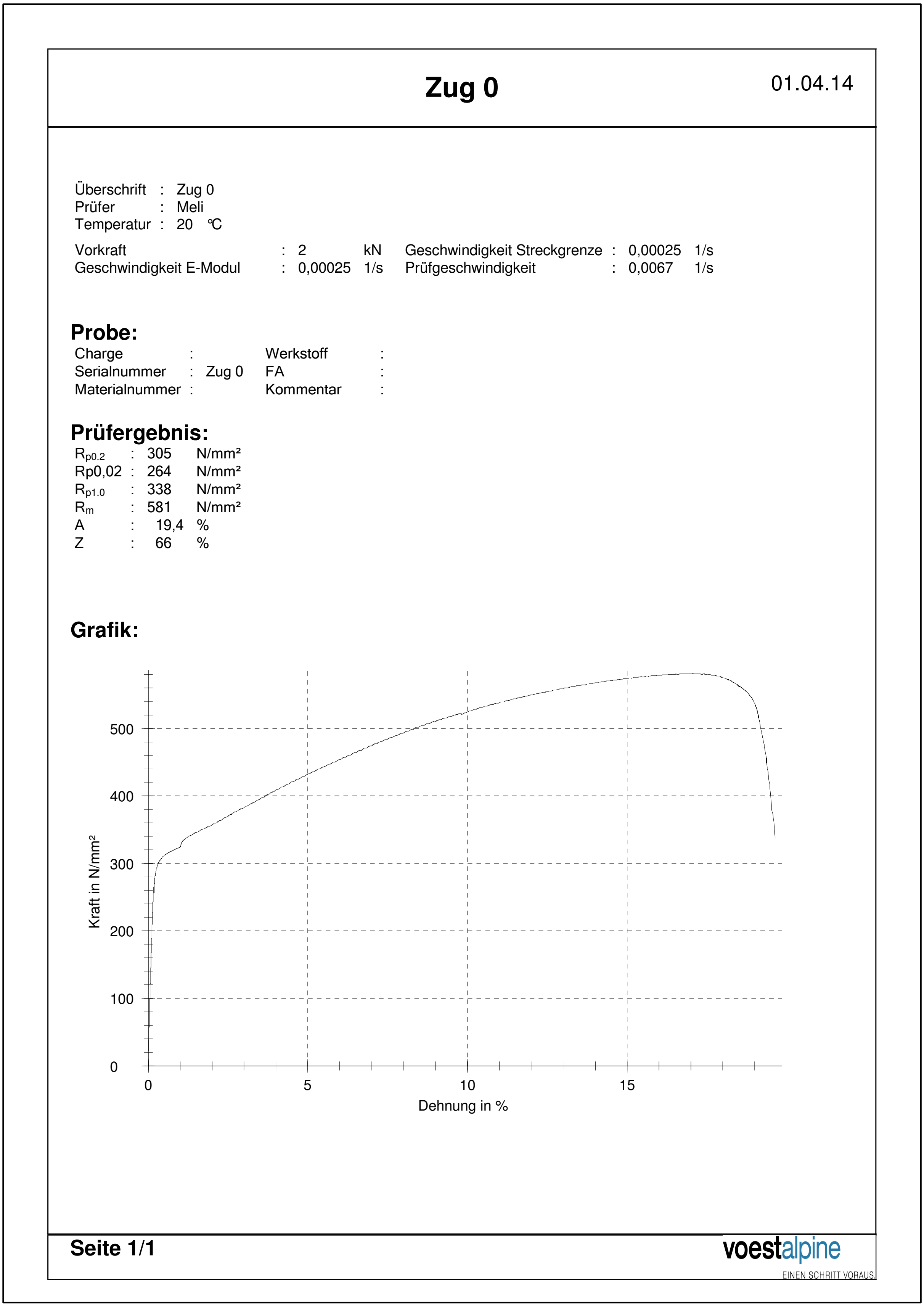


Datum (Date)		Schichtzeit (Shifttime)						Schweißzusatzwerkstoffe (Welding Materials)		Schweißhilfsstoffe (Welding consumables)		Schweißparameter (Welding Parameter)											
2014				Schweißer-Stempelnummer (Welder Stamp No.)	Arbeitsfolge ents. SP (Welding Sequence acc. WPS)	Schweißverfahren (Welding Process)	Schweißposition (Welding Position)	Ø (mm)	Herstellerbezeichnung	Chargen-Seriennr.	Schutzgas/ Spülgas [l/min]	Stromart (Current)	Polung (Polarity)	Stromstärke (Ampere)	Spannung (Volatage)	Ausziehlänge (length of weld bead per unit length electrode)	Vorwärmtemperatur (Preheat Temp.)	Drahtvorschub (m/min)	Zwischenlagentemp. (Interpass Temp.)	Lage (Layer)	Seite (Side)	Raupen (Passes)	Unterschrift Uhrzeit Abnahme-gesellschaft (Inspection Agency)
Tag (Day)	Monat (Month)	von (from)	bis (to)						(Trade Name)	(Heat or. Serial No.)	(Shielding Gas/ Backing Gas [l/min])	= / ~	+ / -	[A]	[V]	[cm]	[°C]		[°C]				
25	01	5⁰⁰		8				5						151	254				70	27	1	10	
			7³⁰					5		4108899				154	253				120	28	1	10	
			[illegible]																				

Bemerkung:

VP-Nr. (PQR-No.): NiBas625/617	**Schweißprotokoll** (Welding Record)	Blatt (Page):	voestalpine GIESSEREI TRAISEN GMBH
pWPS		Datum:	
Auftragsnr. (Order No.):		Name:	

FIGURE 95: WELDING RECORD - SMAW - PAGE 3



Zug 0

01.04.14

Überschrift : Zug 0
Prüfer : Meli
Temperatur : 20 °C

Vorkraft : 2 kN
Geschwindigkeit E-Modul : 0,00025 1/s
Geschwindigkeit Streckgrenze : 0,00025 1/s
Prüfgeschwindigkeit : 0,0067 1/s

Probe:

Charge :
Serialnummer : Zug 0
Materialnummer :
Werkstoff :
FA :
Kommentar :

Prüfergebnis:

$R_{p0.2}$: 305 N/mm²
Rp0,02 : 264 N/mm²
$R_{p1.0}$: 338 N/mm²
R_m : 581 N/mm²
A : 19,4 %
Z : 66 %

Grafik:

Seite 1/1

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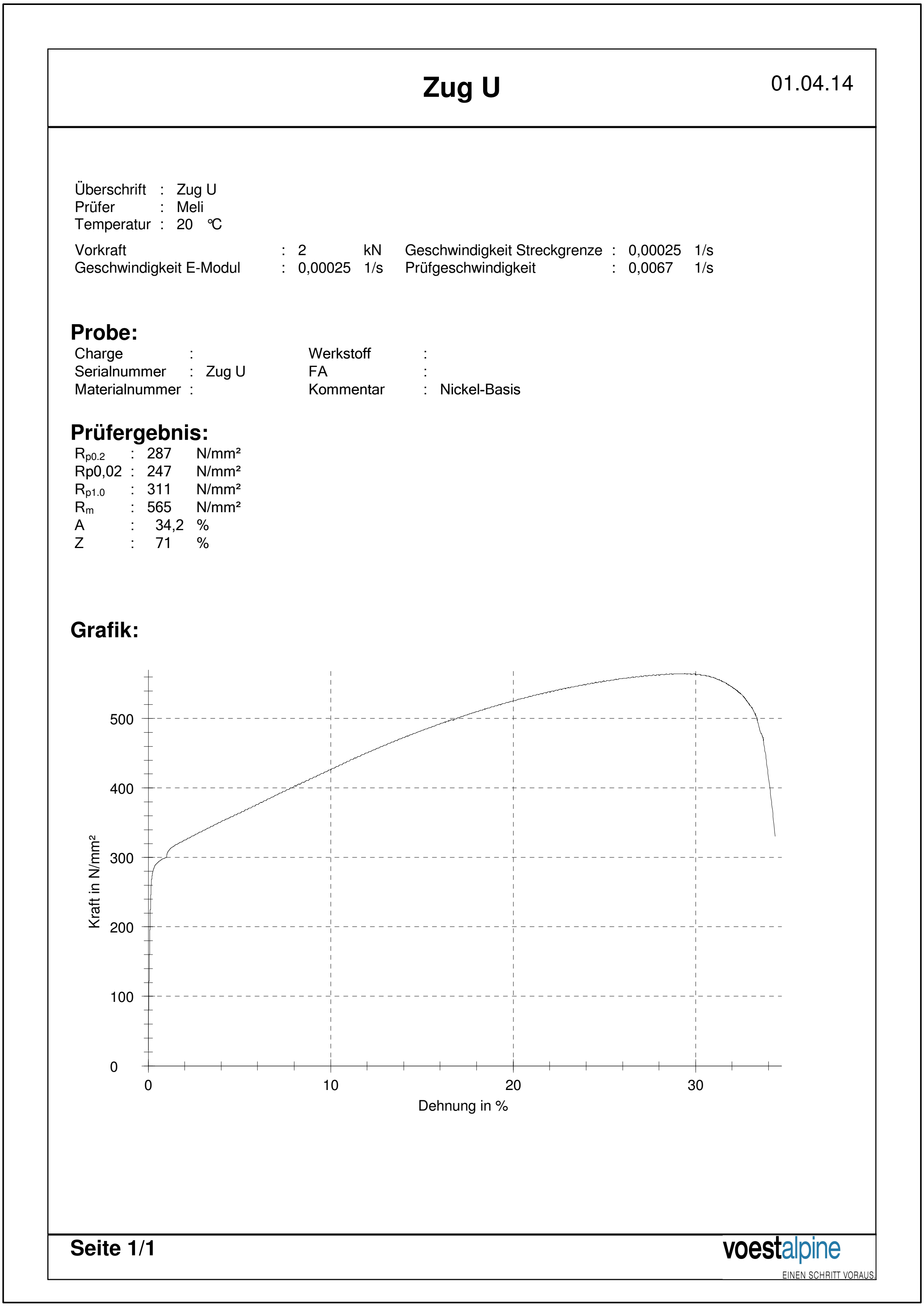
FIGURE 96: TENSILE TEST - SMAW - AS WELDED - TOP



Zug U

01.04.14

Überschrift : Zug U
Prüfer : Meli
Temperatur : 20 °C

Vorkraft : 2 kN
Geschwindigkeit E-Modul : 0,00025 1/s
Geschwindigkeit Streckgrenze : 0,00025 1/s
Prüfgeschwindigkeit : 0,0067 1/s

Probe:

Charge :
Serialnummer : Zug U
Materialnummer :
Werkstoff :
FA :
Kommentar : Nickel-Basis

Prüfergebnis:

$R_{p0.2}$: 287 N/mm²
Rp0,02 : 247 N/mm²
$R_{p1.0}$: 311 N/mm²
R_m : 565 N/mm²
A : 34,2 %
Z : 71 %

Grafik:

Seite 1/1

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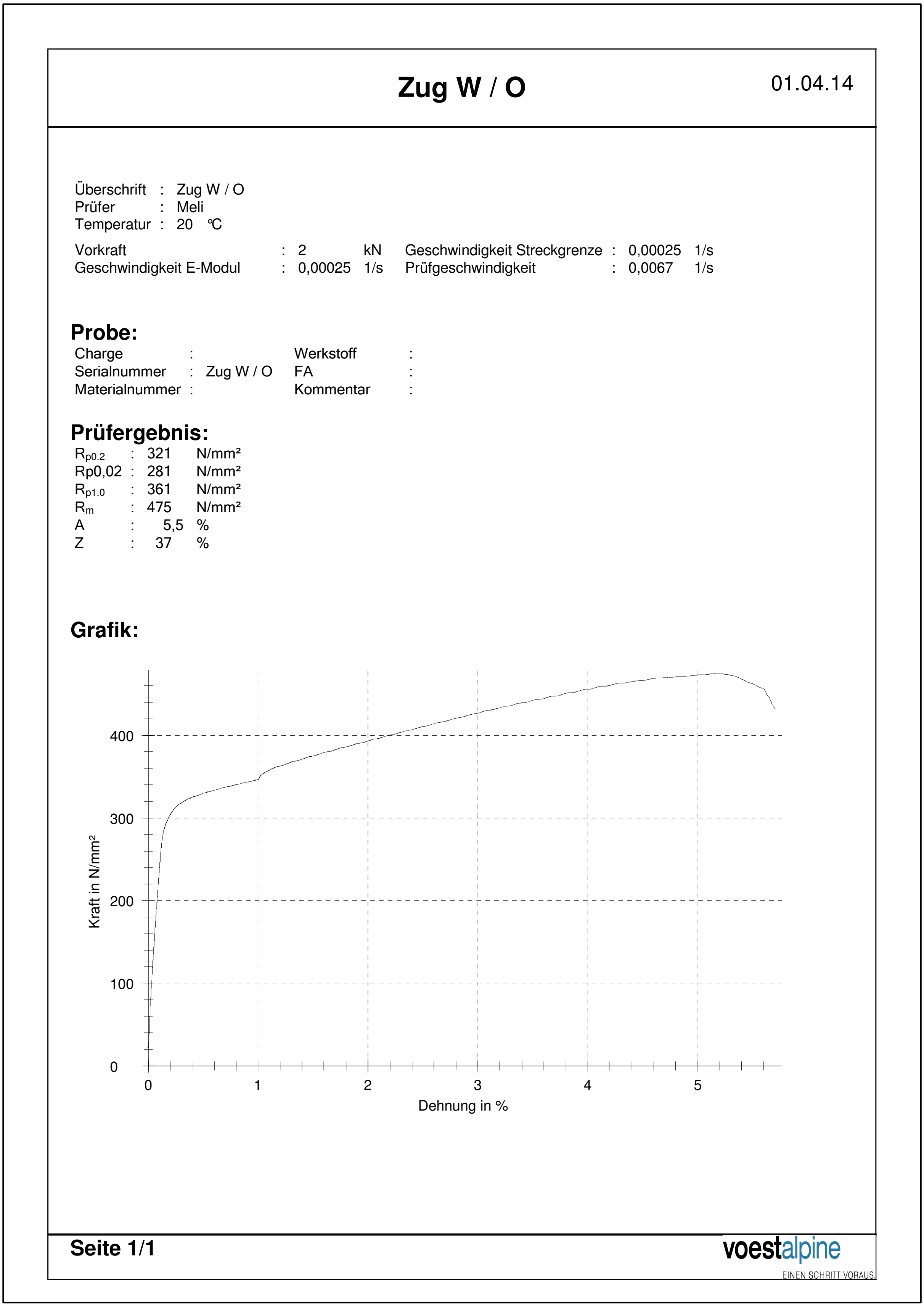
FIGURE 97: TENSILE TEST - SMAW - AS WELDED - BOTTOM



Zug W / O 01.04.14

Überschrift : Zug W / O
Prüfer : Meli
Temperatur : 20 °C

Vorkraft : 2 kN Geschwindigkeit Streckgrenze : 0,00025 1/s
Geschwindigkeit E-Modul : 0,00025 1/s Prüfgeschwindigkeit : 0,0067 1/s

Probe:

Charge : Werkstoff :
Serialnummer : Zug W / O FA :
Materialnummer : Kommentar :

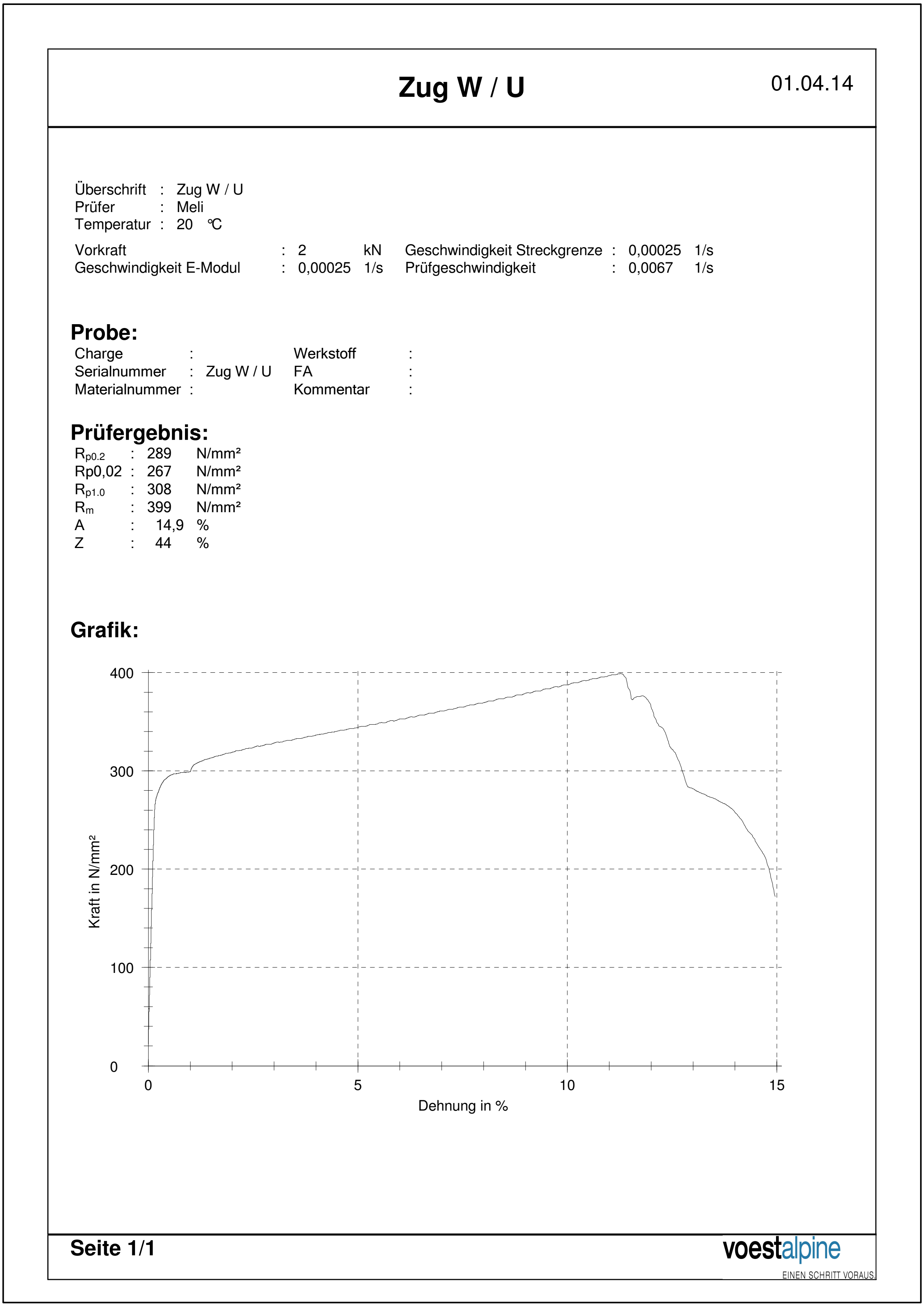
Prüfergebnis:

$R_{p0.2}$: 321 N/mm²
Rp0,02 : 281 N/mm²
$R_{p1.0}$: 361 N/mm²
R_m : 475 N/mm²
A : 5,5 %
Z : 37 %

Grafik:

Seite 1/1

FIGURE 98: TENSILE TEST - SMAW - PWHT - TOP



Zug W / U 01.04.14

Überschrift : Zug W / U
Prüfer : Meli
Temperatur : 20 °C

Vorkraft : 2 kN Geschwindigkeit Streckgrenze : 0,00025 1/s
Geschwindigkeit E-Modul : 0,00025 1/s Prüfgeschwindigkeit : 0,0067 1/s

Probe:

Charge : Werkstoff :
Serialnummer : Zug W / U FA :
Materialnummer : Kommentar :

Prüfergebnis:

$R_{p0.2}$: 289 N/mm²
Rp0,02 : 267 N/mm²
$R_{p1.0}$: 308 N/mm²
R_m : 399 N/mm²
A : 14,9 %
Z : 44 %

Grafik:

Seite 1/1

FIGURE 99: TENSILE TEST - SMAW - PWHT - BOTTOM

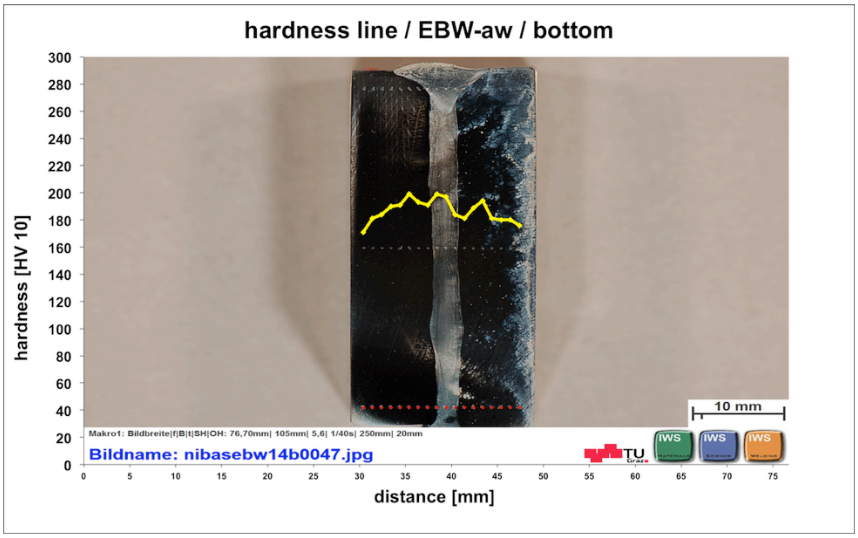


FIGURE 100: HARDNESS LINE EBW-AW BOTTOM

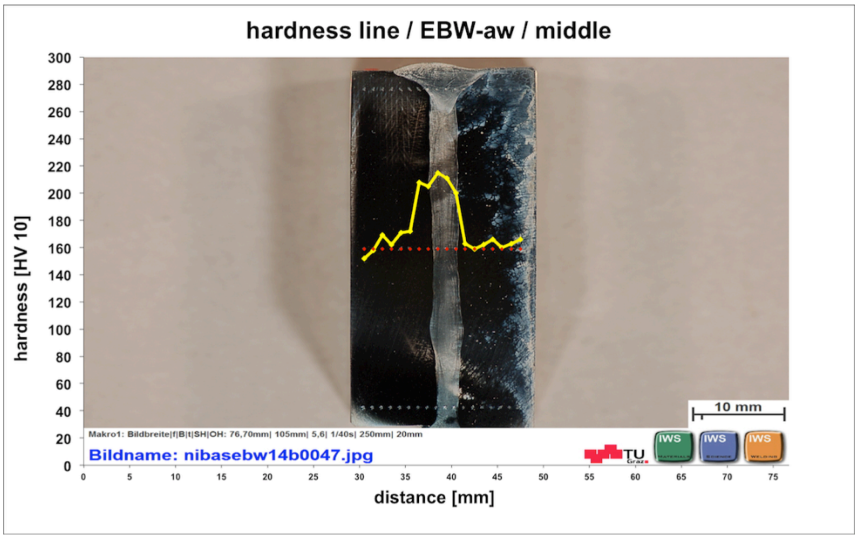


FIGURE 101: HARDNESS LINE EBW-AW MIDDLE

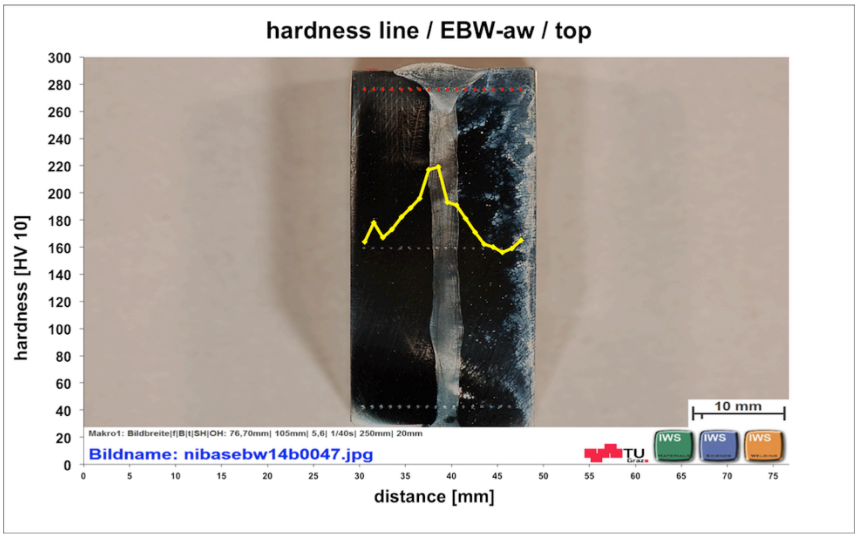


FIGURE 102: HARDNESS LINE EBW-AW TOP

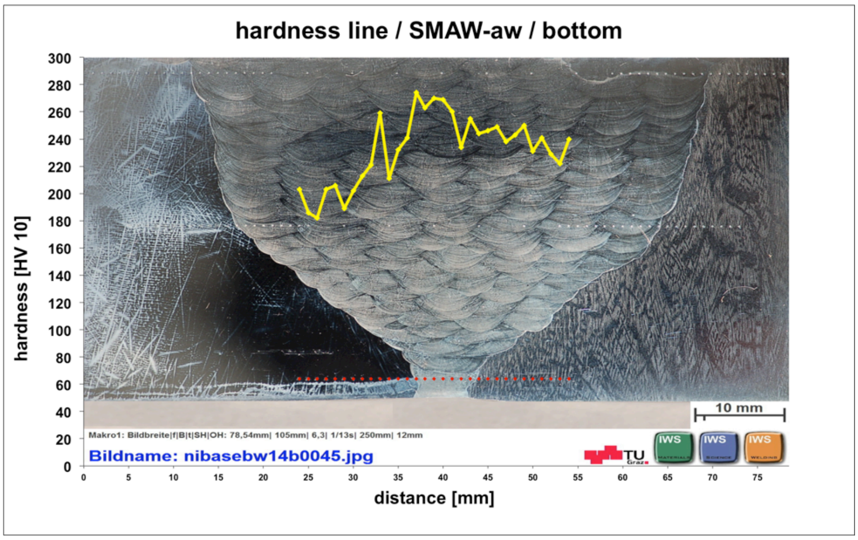


FIGURE 103: HARDNESS LINE SMAW-AW BOTTOM

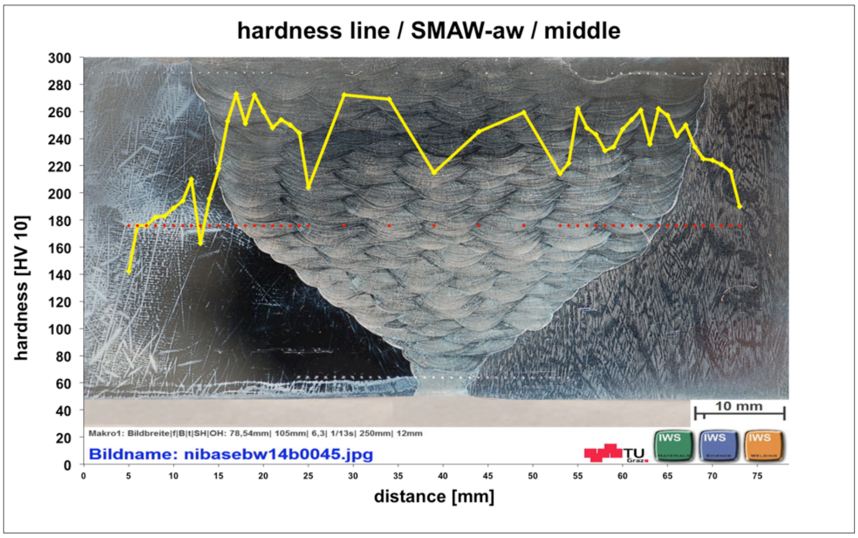


FIGURE 104: HARDNESS LINE SMAW-AW MIDDLE

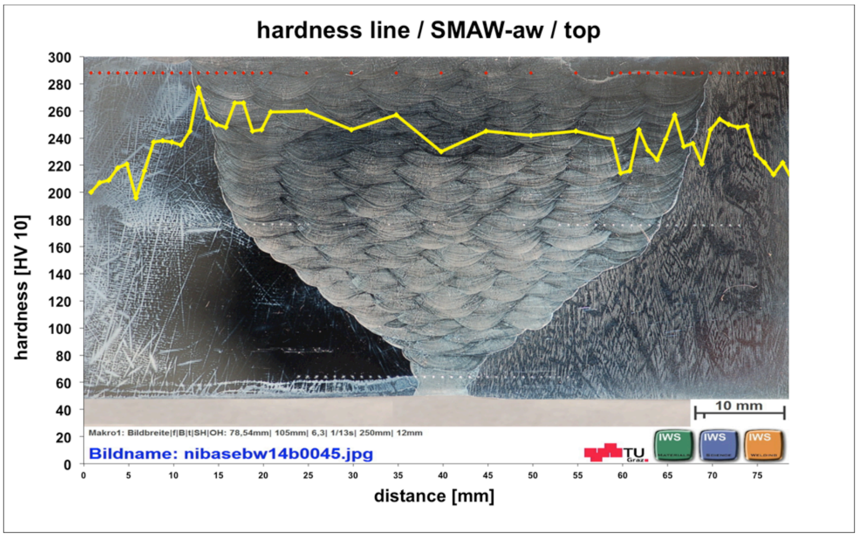


FIGURE 105: HARDNESS LINE SMAW-AW TOP

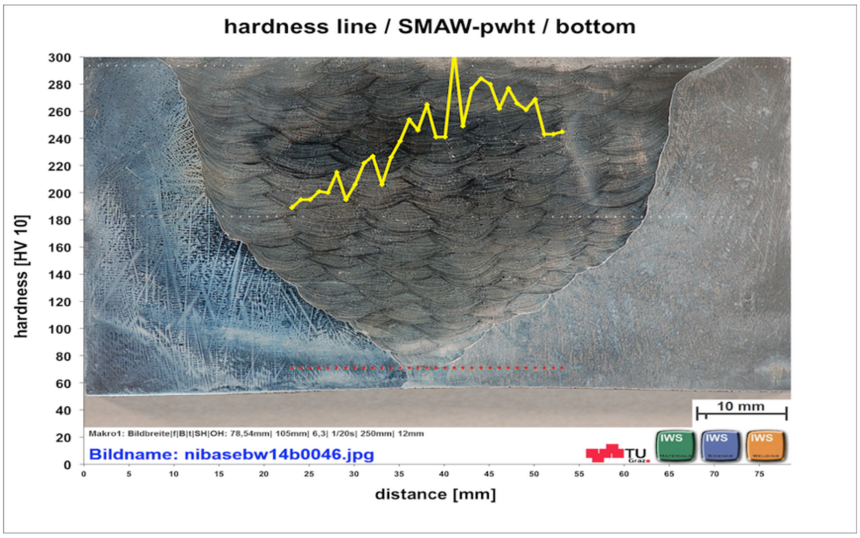


FIGURE 106: HARDNESS LINE SMAW-PWHT BOTTOM

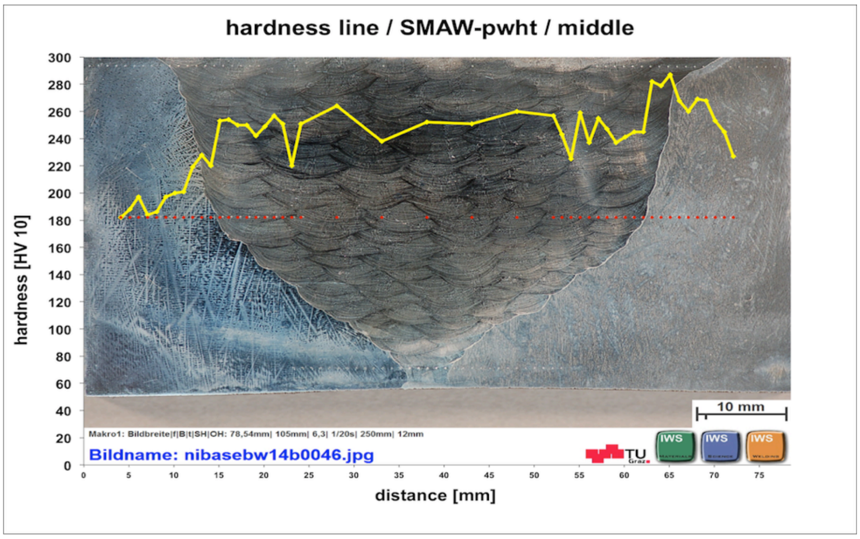


FIGURE 107: HARDNESS LINE SMAW-PWHT MIDDLE

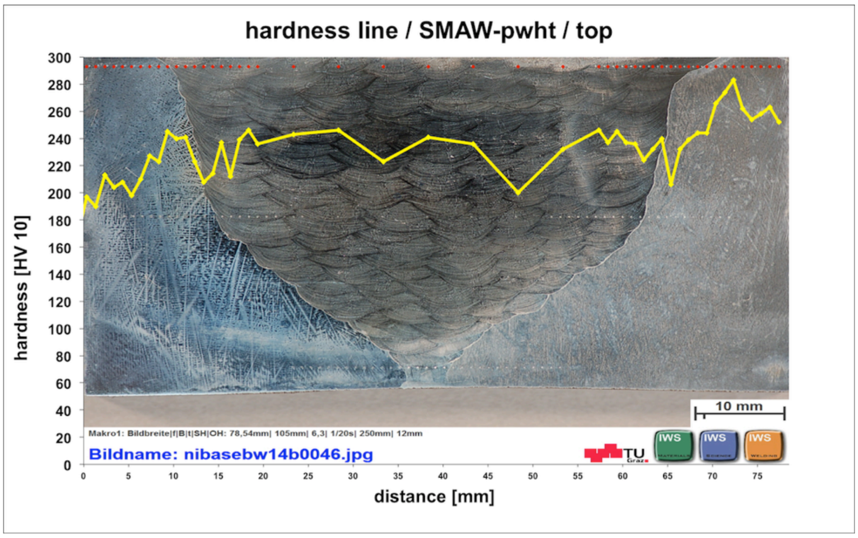


FIGURE 108: HARDNESS LINE SMAW-PWHT TOP